Properties and Improved Space Survivability of POSS Polyimides

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Outline

- Lower Earth Orbit Environment
- Assessment of state-of-the-art Space Polyimides.
- POSS: Polyhedral Oligomeric Silsesquioxane
- POSS Kapton Polyimides
- Ground Based Tests: Atomic Oxygen (AO) Erosion Studies
- Self Forming / Self Healing Silica Passivation Layer
- Modeling and Simulation of AO attack on POSS
- Flight Tests: MISSE 4, 5, 6
- Thermal and Mechanical Properties
- Summary and Conclusions
- Acknowledgments

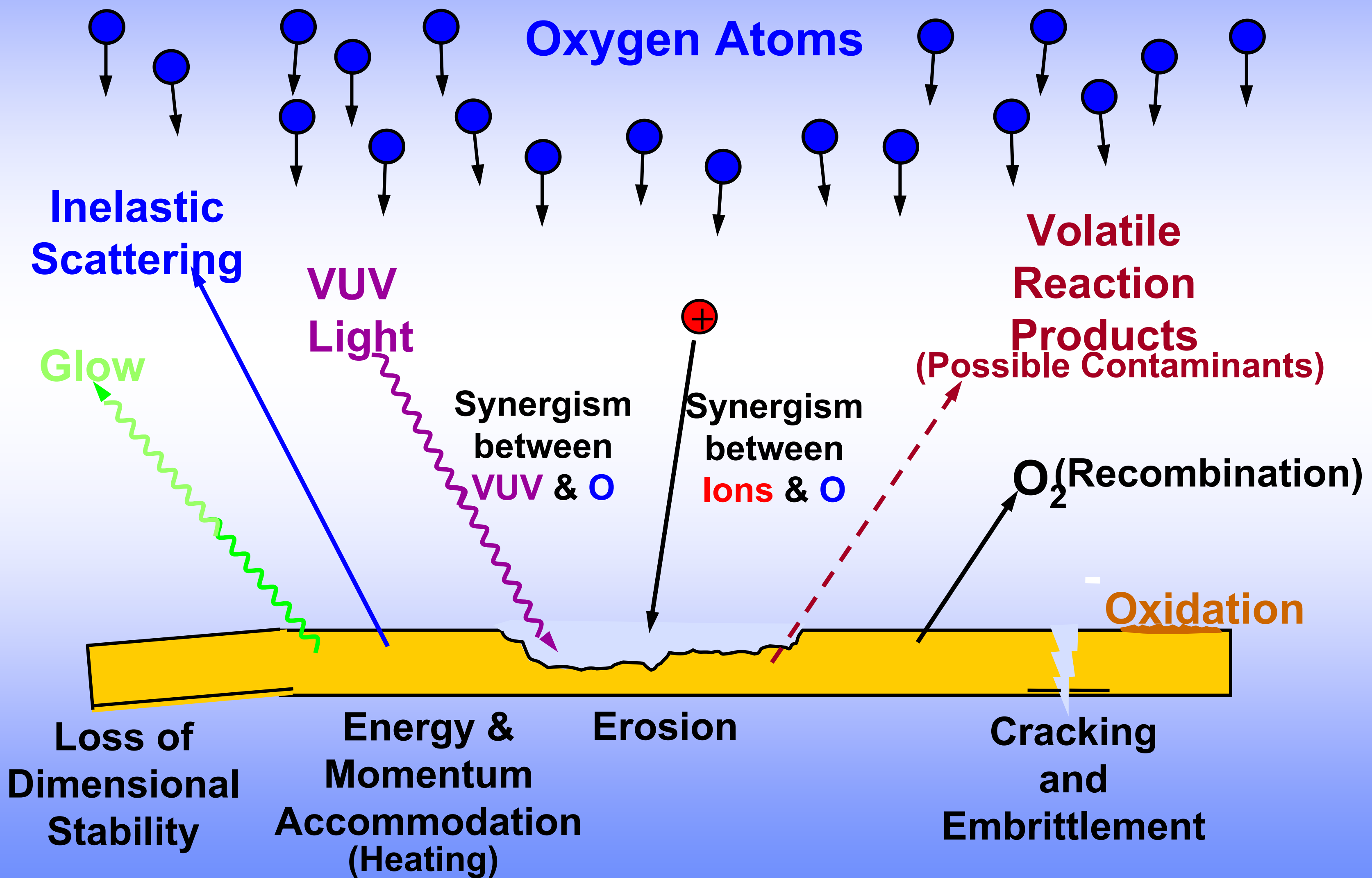
Lower Earth Orbit Environment

- **Atomic Oxygen (AO) Erosion of Kapton in LEO is a serious threat to spacecraft durability.**

- **As a space vehicle orbits the Earth at orbital speed (7.8 km/sec at low altitudes) it undergoes energetic collisions with atoms and molecules in the orbital environment.**

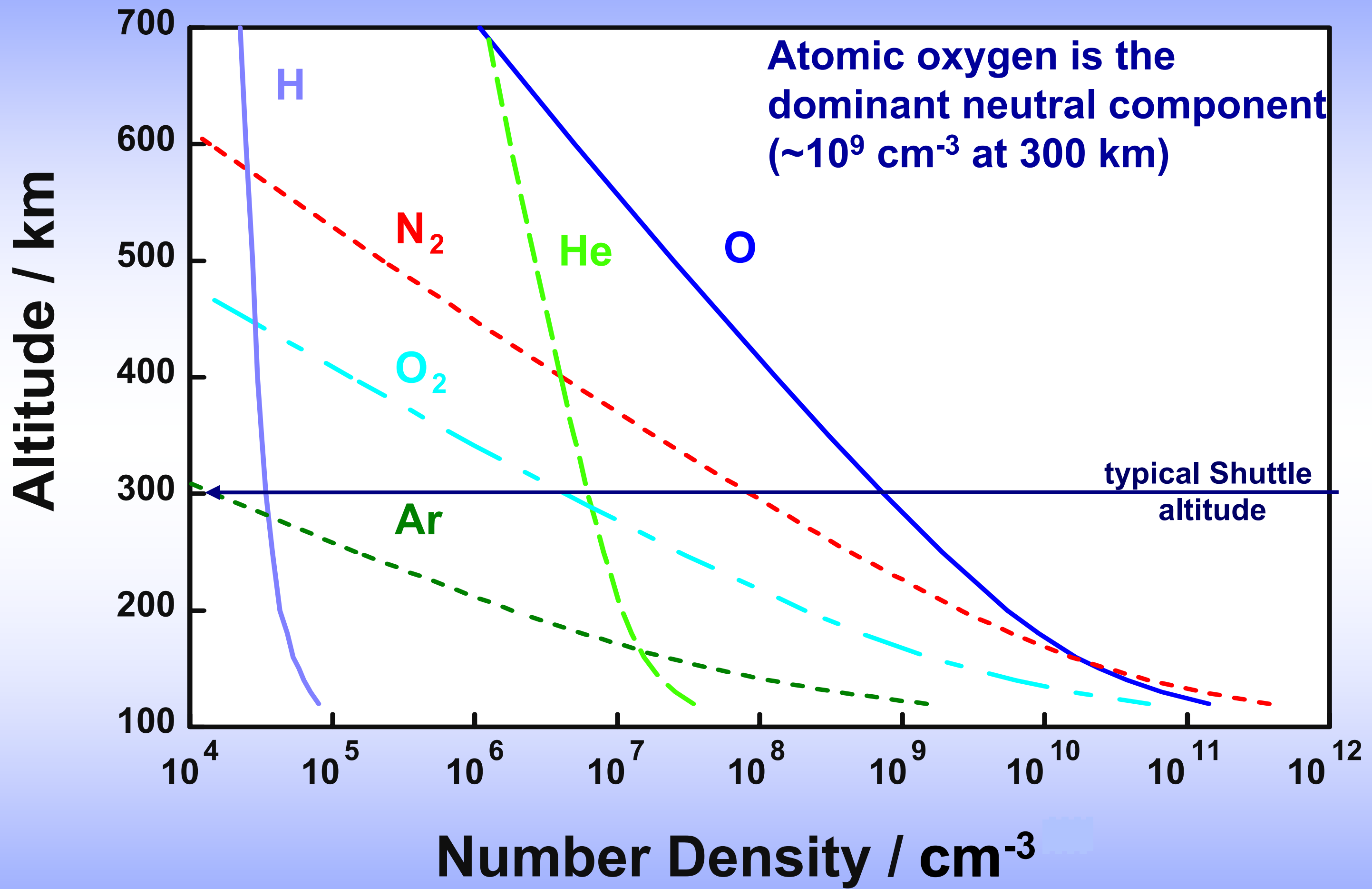
- **AO is the dominant species in the outer ionosphere from 200-700 km, becoming as much as 90 % of the atmosphere at 500 km, a typical altitude for the International Space Station and future space platforms.**

Atomic Oxygen and Synergistic Effects on Materials



Courtesy of Dr. Timothy Minton, Montana SU

Neutral Composition of Earth's Upper Atmosphere



Roble, in <u>The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory</u>, Geophysical Monograph 87, pp 1 – 21, 1995.

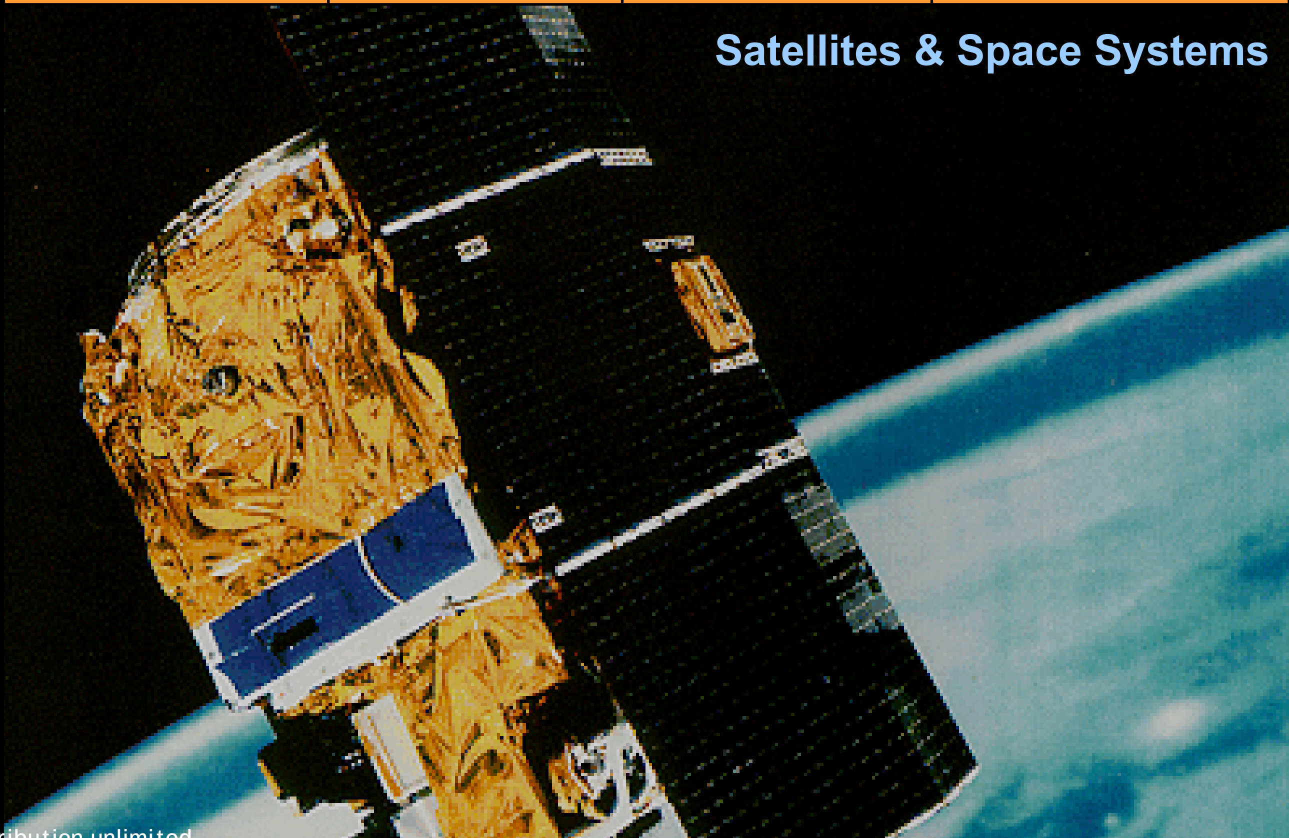
Courtesy of Dr. Timothy Minton, Montana SU

Technical Problem
Atomic Oxygen in Lower Earth Orbit

LEO Environment
(Altitudes of 200 to 1500 km)

- Atomic Oxygen (AO): ~10^{6} - 10^{8} atoms/cm^3 , up to 90 % of the atomosphere at 500km (typical altitude for international space station).
- Actual AO flux on spacecraft ~10^{12} – 10^{14} atoms/cm^2•s
- AO Collision energy ~ **5eV (7.8 km/sec)** (C-C bond energy ~ 4 eV, C-N ~ 3eV, **Si-O ~ 8.3eV**)
- Low-energy and high energy charged particles.
- Thermal cycling -50 to 150°C
- Solar VUV and UV radiation (~ 100 – 400 nm)
- Bond scission and radical formation can lead to embrittlement.

Bond	Dissociation Energy (EV)	λ (nm)	Material
$-C_6H_4-C(=O)-$	3.9	320	Kapton®
C-N	3.2	390	Kapton®
Si-O	8.3	150	Nanocomposite



State-of-the-Art Space Polyimides

- Kapton H Protected by a sputtered on Silica layer (SiO_2).

- Inherent problems in protective Silica layer:
- Defects from surface anomalies occurring during deposition process.
- Cracks and microdefects due to micrometeoroid and debris
- bombardment in LEO. Underpinning Effect.
- Results:
- Exposure of underlying Kapton layer.

- Lifetime of Kapton H protected by sputtered on silica layer:

- Example:
- Hubble Space Telescope:
- Altitude = 610 km.
- AO fluence exposure: 7.59 x 10^{20} atoms/cm^2 for 3.6 years.
- Revisited every 2-3 years for maintenance including replacement of
- solar arrays and patching of multilayer insulation blankets.

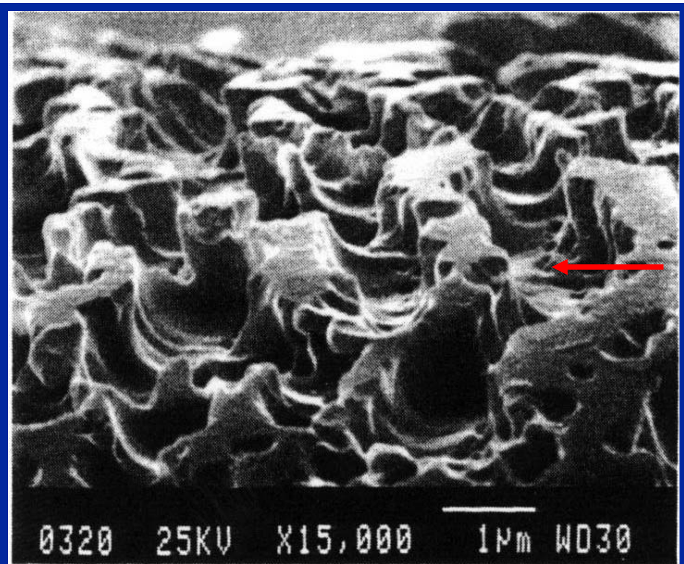
AO undercutting of Aluminized-Kapton Multilayer Insulation flown on LDEF

LDEF Satellite:

Long Duration Exposure Facility.

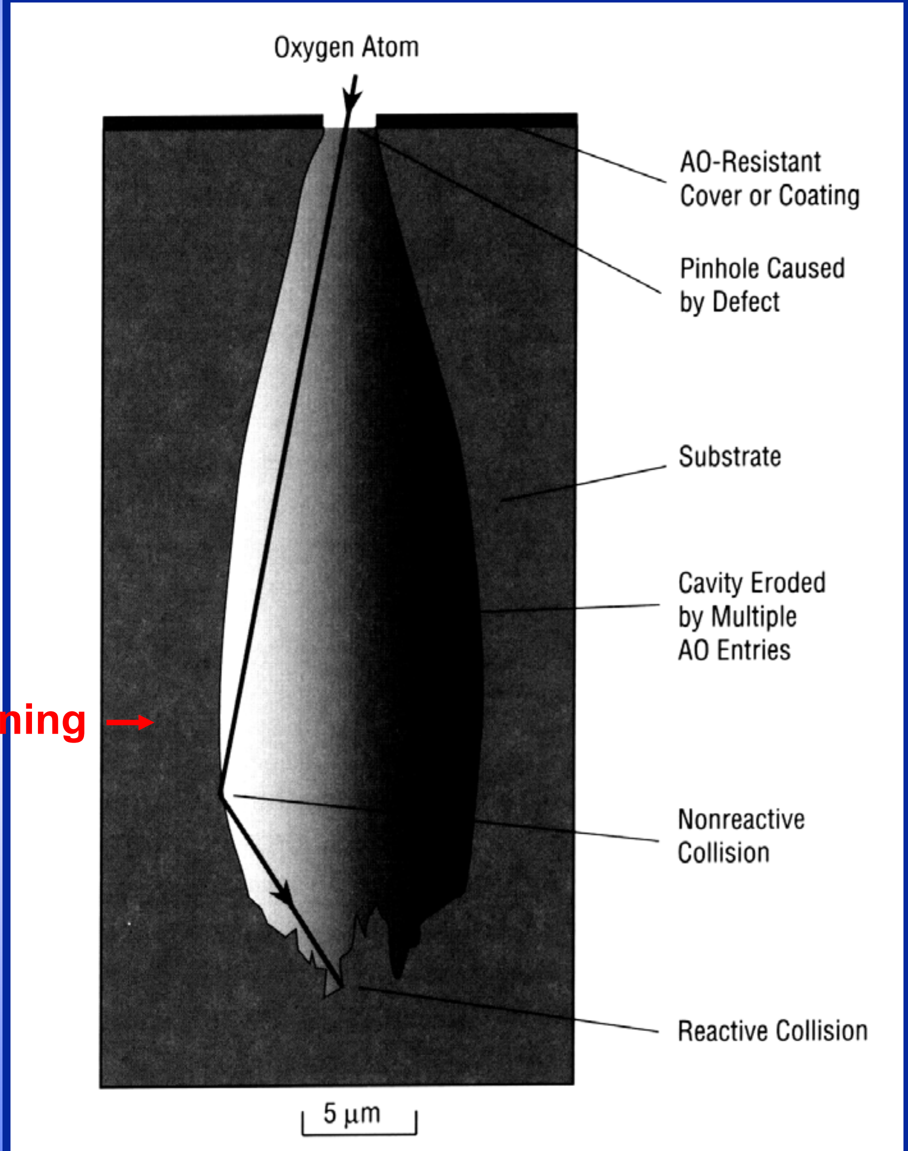
Total AO Exposure: 9 x 10^{21} atoms/cm^2

Depths of >0.0127cm (> 5mils) of Kapton sheets were eroded away after 5.8 yrs in LEO on the ram AO surface of the LDEF



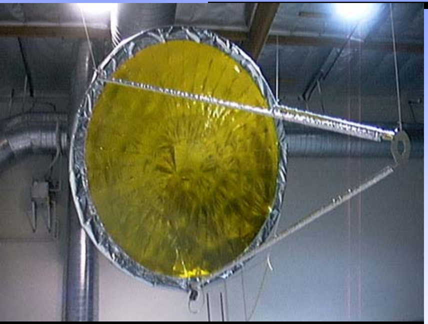
Scanning Electron Micrograph Of Kapton MLI Surface.

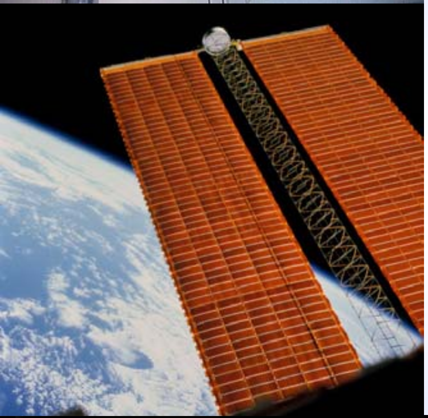
Underpinning Effect



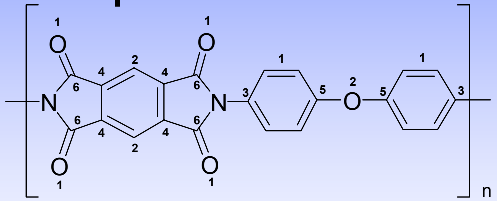
DISTRIBUTION A. Approved for public release; distribution unlimited. DeGroh, K.K., Banks, B.A., J. Spacecraft and Rockets, Vol. 31, No. 4, (1994)

Goal



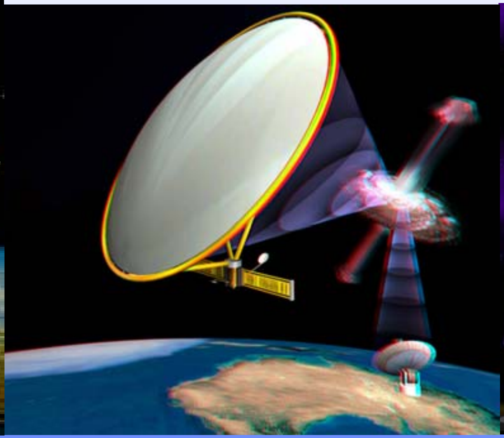


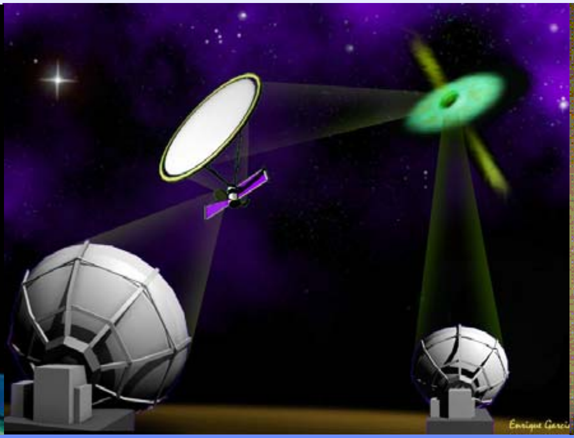
Kapton

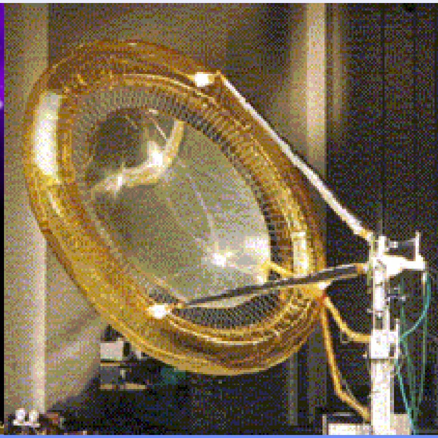


Our goal is to create an efficient drop-in replacement for Kapton that:

1. Has increased space survivability due to **resistance to atomic oxygen**, thermal cycling, solar UV and VUV radiation, protons and electrons.
2. Is Self-Passivating and **Self-Healing** based on hybrid . organic/ inorganic nanocomposite incorporation
3. Has superior optical properties, low solar absorptance, high thermal reflectance
4. Has excellent mechanical thermal properties.

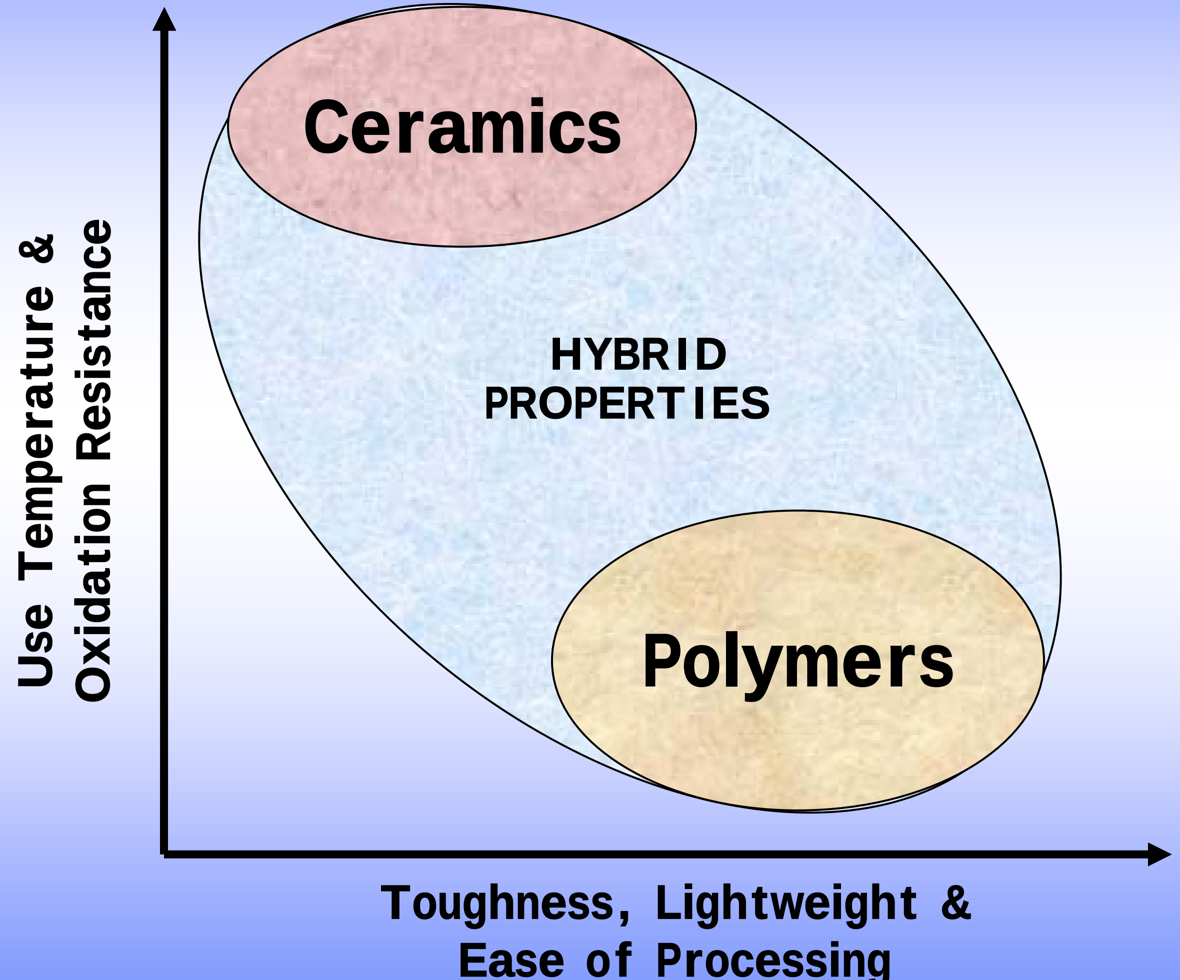






Hybrid Inorganic/Organic Polymers

Goal: Develop High Performance Polymers that REDEFINE material properties



- **Hybrid plastics bridge the differences between ceramics and polymers**

Why Use POSS?

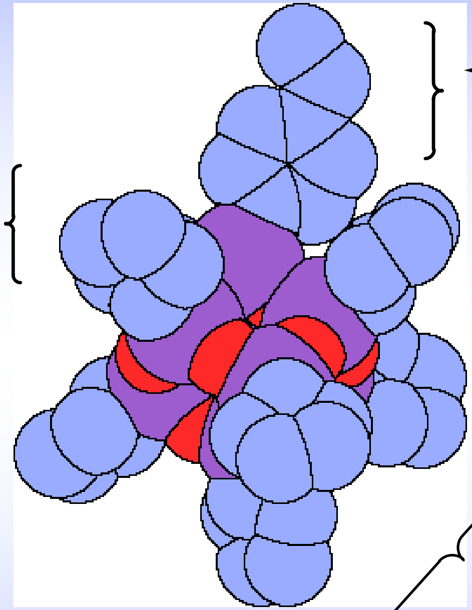
- Multifunctionality – including no negative effects on processing (or can even get improvements)

- Properties previously not attainable (extended temp range, flame retardancy)

- Turnkey Utility

- <u>Control</u> of molecular architecture

Anatomy of a POSS Nanostructure



May posess one or more functional groups suitable for polymerization or grafting.

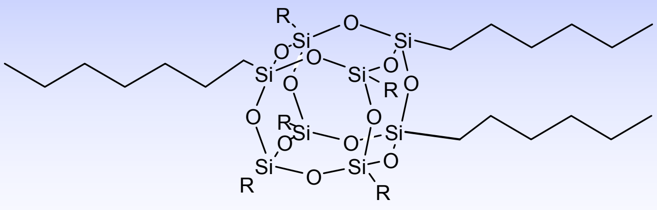
Nonreactive organic (R) groups for solubilization and compatibilization.

Nanoscopic in size with an Si-Si distance of 0.5 nm and a R-R distance of 1.5 nm.

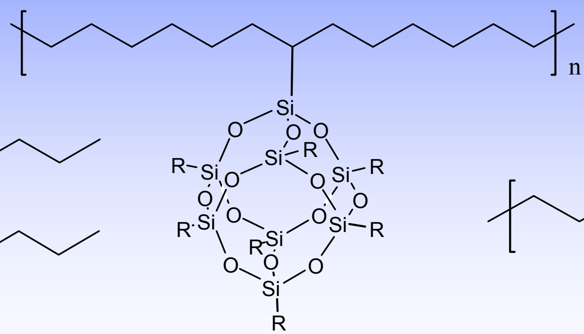
Thermally and chemically robust hybrid (organic-inorganic) framework.

Precise three-dimensional structure for molecular level reinforcement of polymer segments and coils.

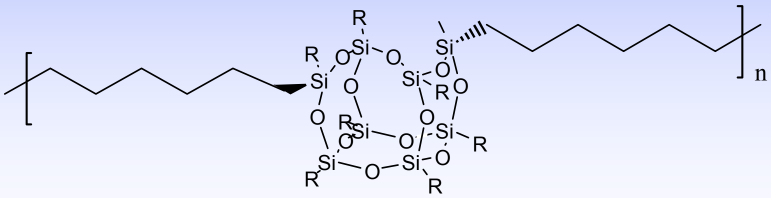
POSS Incorporation into Polymers



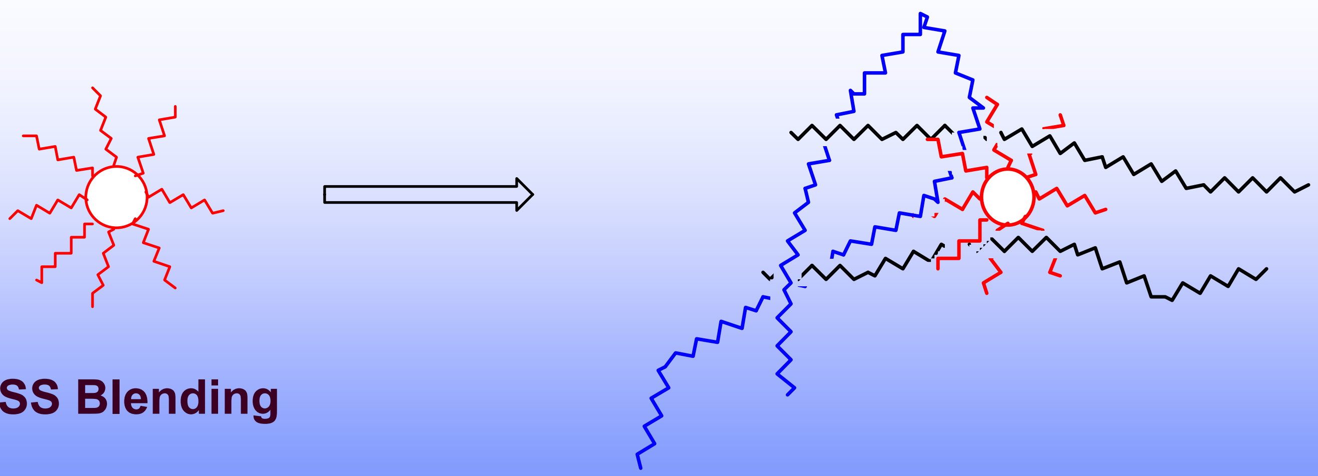
Cross-linker



Pendant Polymer

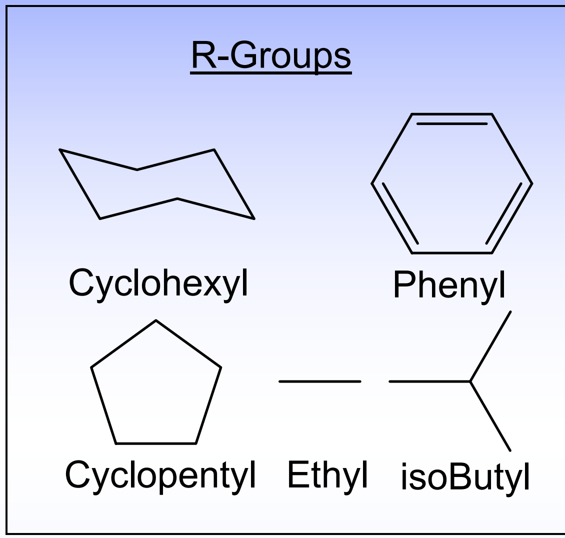


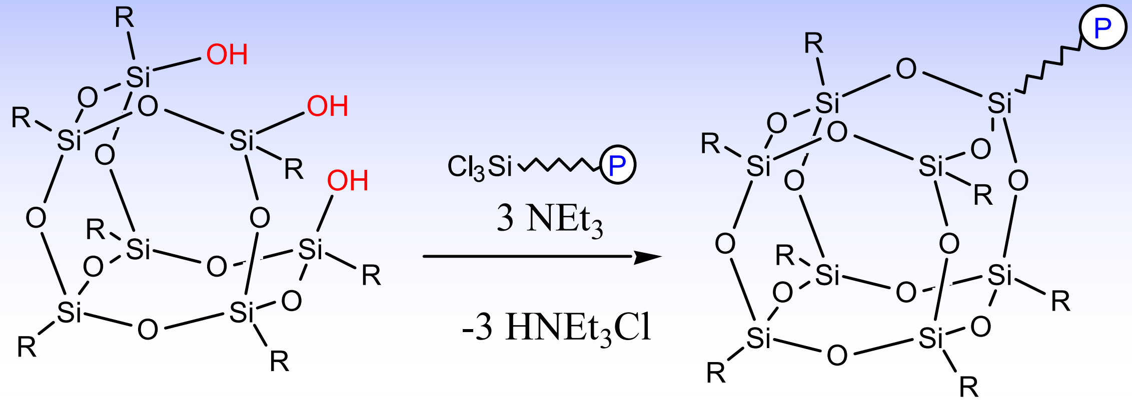
Bead Copolymer



POSS Blending

New Polymer Feedstock Technology



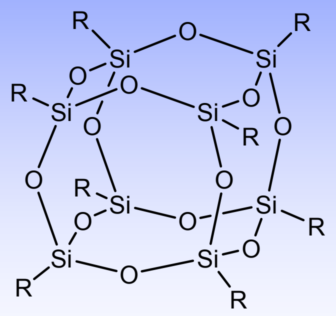


Halides	Nitriles	Silanes	Styryls
Alcohols	Amines	Silanols	a-olefins
Esters	Isocyanates	Silylchlorides	Acrylics
Bisphenols	Epoxides		Norbornenyls

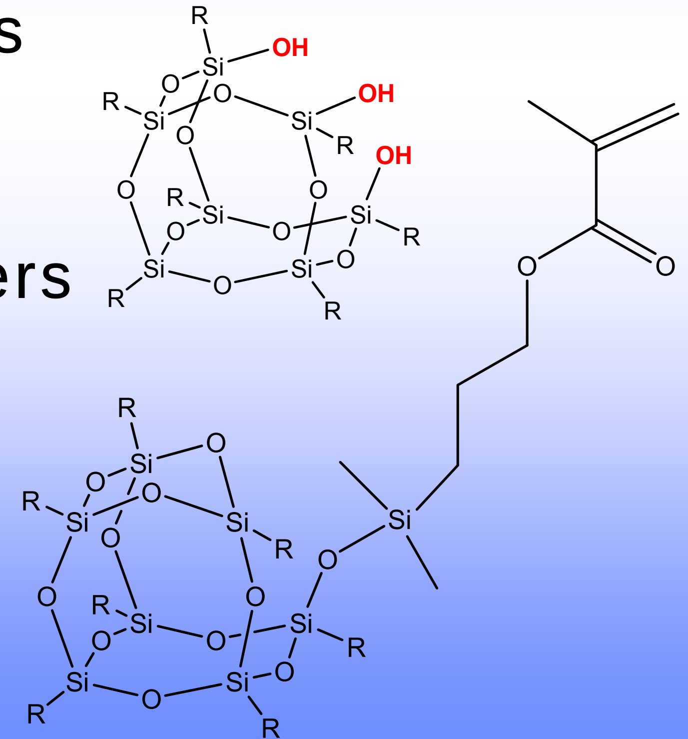
POSS-based macromers are available through either **Gelest** or **Aldrich**

POSS technology is commercialized by **Hybrid Plastics** in Fountain Valley CA

POSS: Where We Were (1996)



- Cost: $5,000-$10,000/lb
- Volume: ~20 lbs/yr
- Production time: min 11 days,
- max 6 months



- Versatility: ~6 POSS feedstocks
- ~30 POSS macromers
- No successful POSS blends
- Made only by U.S. Government

Why POSS and Why Nano?

1 mm
- Sewing Needle
- Razor Blade Thickness

100 µm
- Human Hair
- Most Cells & Fibers

10 µm

1 µm
- Bacteria, Fillers & Polymer Morphology

100 nm
- Viruses & Nanofillers

10 nm
- POSS® Building Blocks

1.0 nm
- Macromolecules

0.1 nm
- Atoms / Small Molecules

Field	Property	Critical Length
Electronics	Tunneling	1-100 nm
Optical	Quantum Well	1-100 nm
	Wave Decay	10-1000 nm
Polymers	Primary Structure	0.1-10 nm
	Secondary Structure	10-1000 nm
Mechanics	Dislocation Interaction	1-1000 nm
	Crack Tip Radius	1-100 nm
	Entanglement Rad.	10-50 nm
Therm-Mech.	Chain Motion	0.5-50 nm
Nucleation	Defect	0.1-10 nm
	Critical Nucleus Size	1-10 nm
	Surface Corrugation	1-10 nm
Catalysis	Surface Topology	1-10 nm
Biology	Cell Walls	1-100 nm
Membranes	Porosity Control	0.1-5 nm

Nanostructured™ POSS Chemicals Physical Form of Products

Hybrid Plastics™

Crystalline Solids — Wide melting range 24°C to 400°C+

Waxes

Liquids & Oils — Wide viscosity range 40cSt. to 400cSt

>120 POSS Monomers, Polymers and Feedstocks Available

What Property Enhancements Can You Get From Using POSS?

increased T_g

increased T_{dec}

oxidation resistance

reduced flammability

extended use temperature range

altered mechanicals

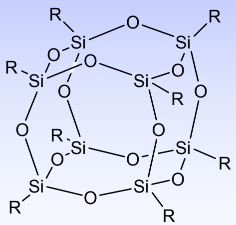
reduced heat evolution

lower thermal conductivity

lower density

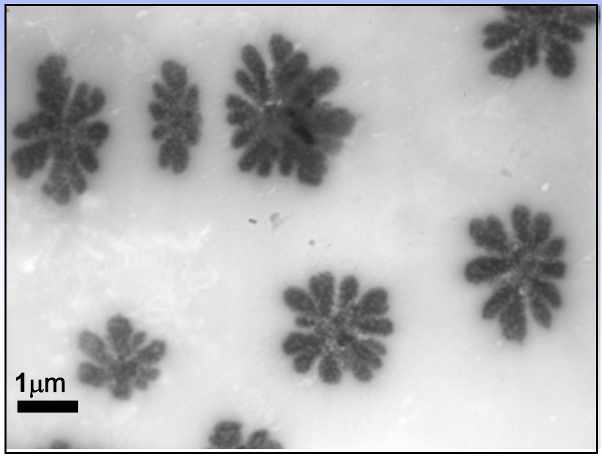
How to use POSS (Blends or Drop-In Nanofillers)

50 Wt % POSS Blends in 2 Million MW PS

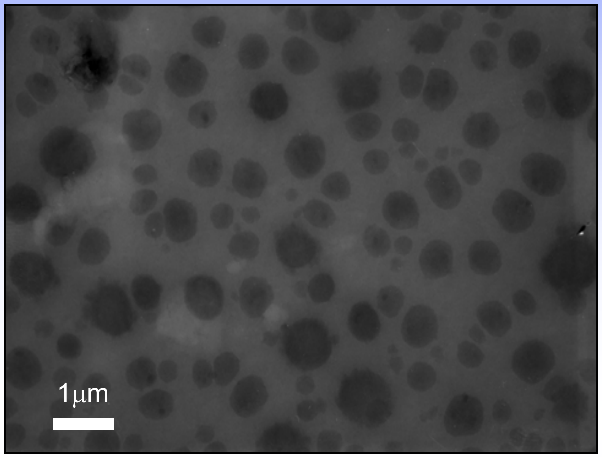


R = cyclopentyl

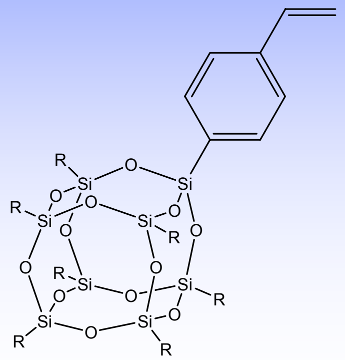
Cp_8T_8



Domain Formation

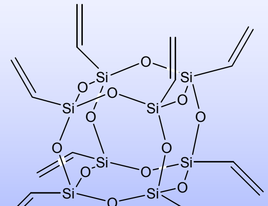


Partial Compatibility

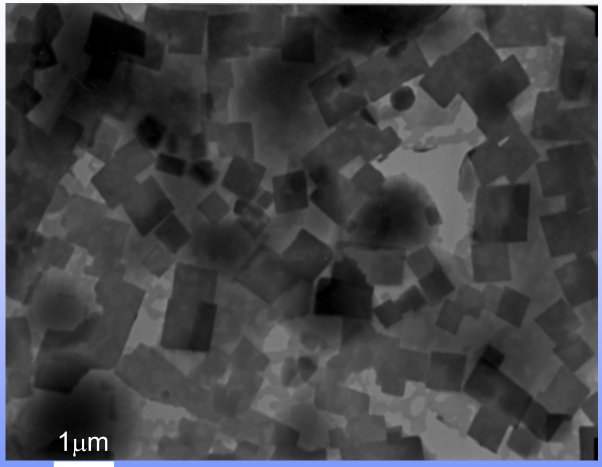


R = cyclopentyl

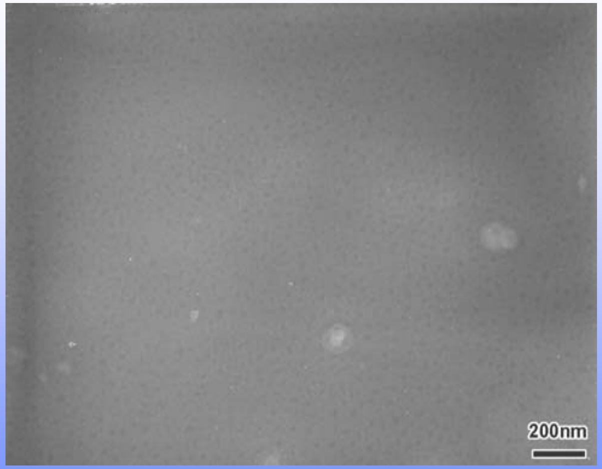
Cp_7T_8Styryl



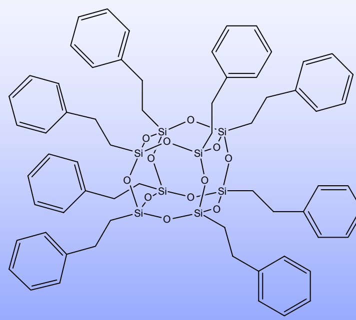
Vi_8T_8



Immiscible POSS Crystallites



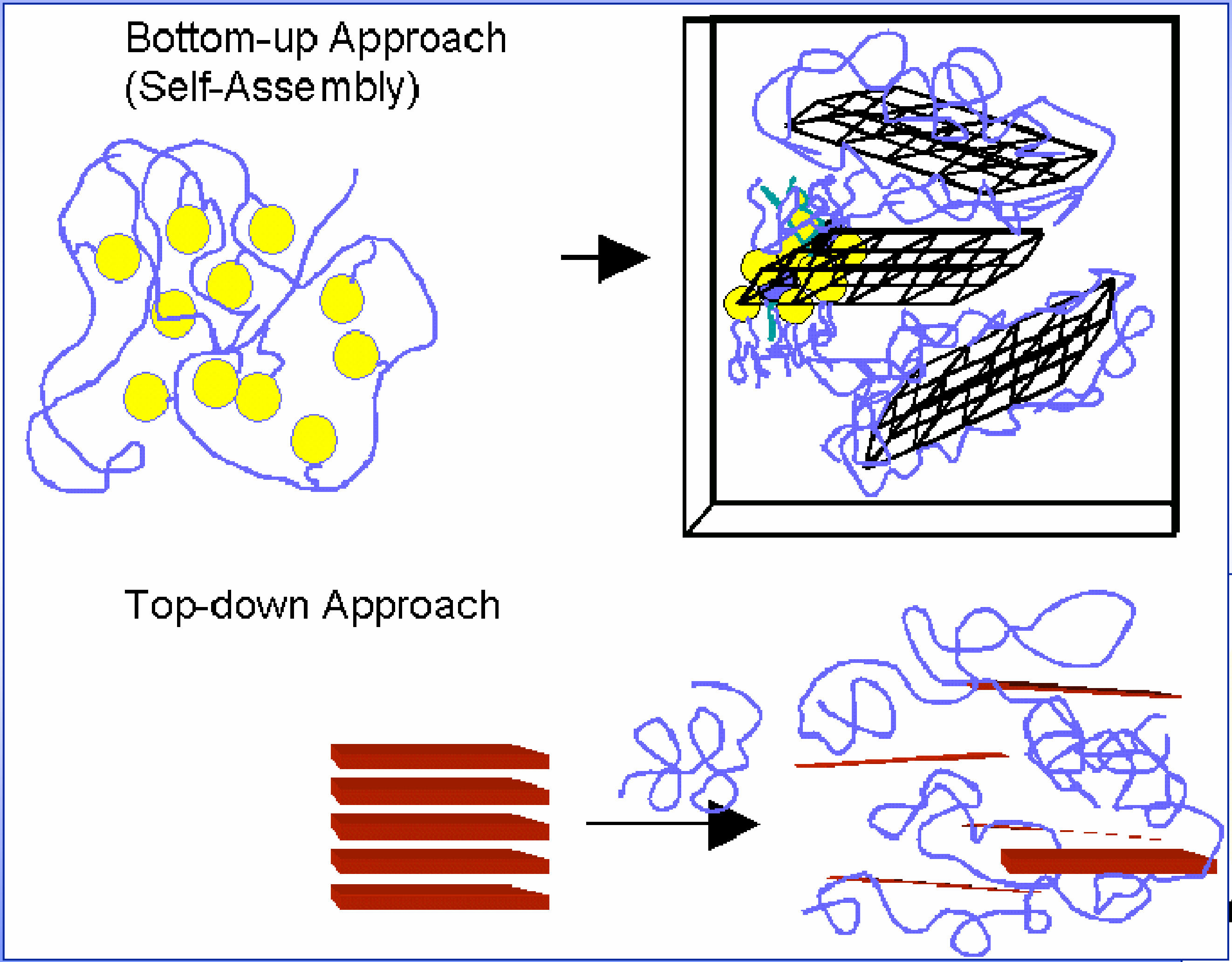
Complete Compatibility-
POSS Nanodispersion/Transparent

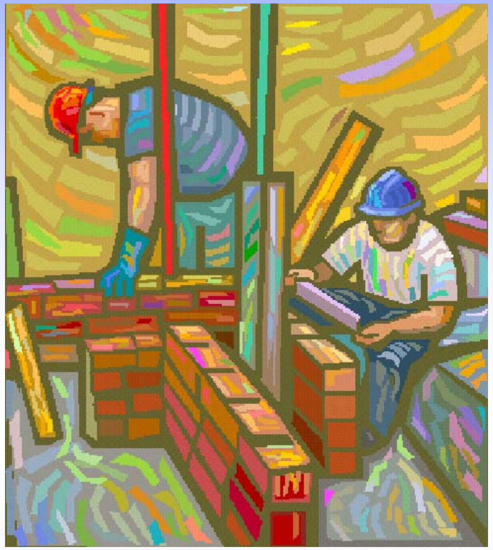


$Phenethyl_8T_8$

Blanski, et al., *Polymer Preprints*, **2000**. 41(1): p. 585.

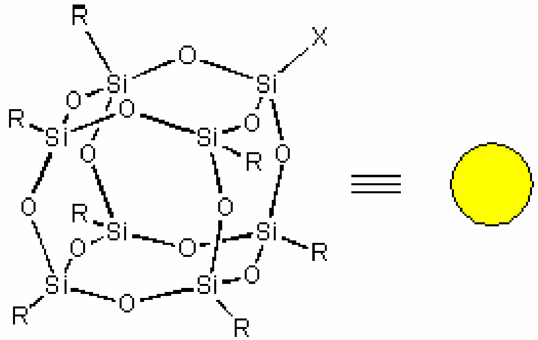
Coughlin Building Block Model (POSS Blends & Copolymers)



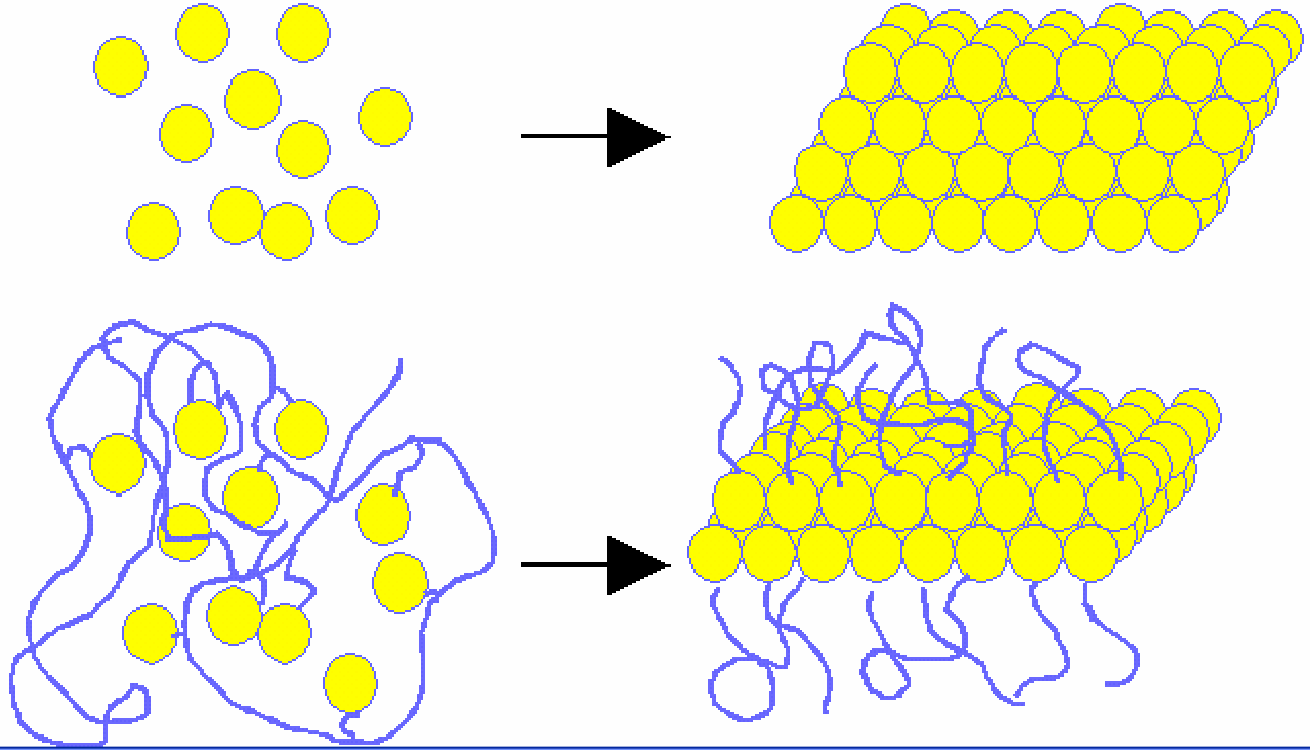


Bryan Coughlin-UMass

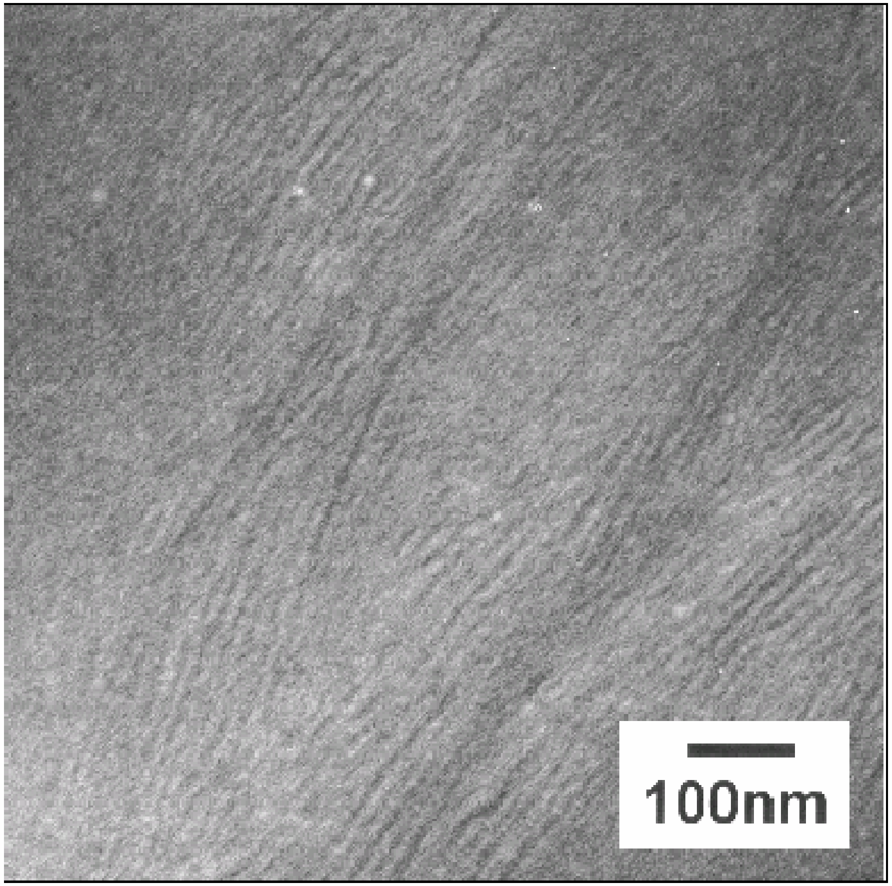
Coughlin Model Continued (building from the ground up)



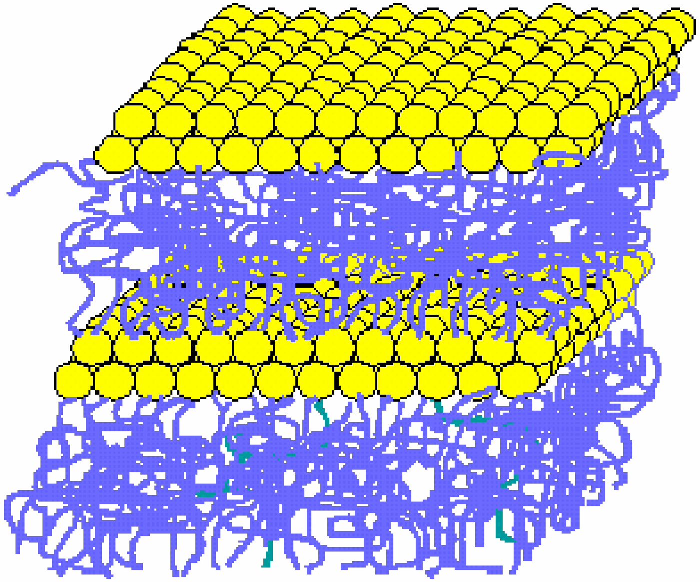
1. As a solid, POSS crystallizes



Nanoengineering with POSS

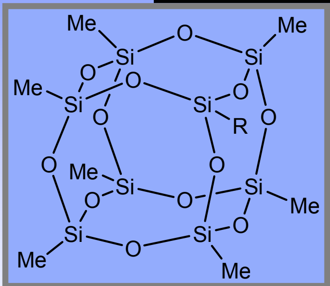


PBD-POSS4 (43wt%POSS)



Bryan Coughlin-UMass

Prof. Andre Lee i-PP/POSS Blends

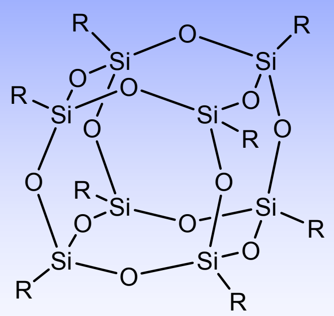


	Dow data	Neat *i*-PP (processed)	*i*-PP blended 2 wt% $Methyl_8T_8$	*i*-PP blended 5 wt% $Methyl_8T_8$	*i*-PP blended 10 wt% $Methyl_8T_8$
Tensile Strength @ Yield; ASTM D638	5000 psi (34.5 MPa)	4800 psi (33.0 MPa)	5000 psi (34.5 MPa)	5100 psi (35.1 MPa)	5200 psi (35.8 MPa)
Flexural Modulus (0.05 in/min); ASTM D790A	240,000 psi (1.655 GPa)	235,000 psi (1.620 GPa)	251,000 psi (1.730 GPa)	255,000 psi (1.757 GPa)	262,000 psi (1.80 GPa)
HDT @ 66 psi, as injected; ASTM D648	210 ^oF (99 ^oC)	210 ^oF (99 ^oC)	221 ^oF (105 ^oC)	239 ^oF (115 ^oC)	255 ^oF (124 ^oC)
Impact Izod @25C ASTM D256A	0.5 ft-lb/in	0.55 ft-lb/in	0.55 ft-lb/in	0.62 ft-lb/in	0.75 ft-lb/in

- **The above data (other than Dow's data) is an average of at least 10 samples for each test with acceptable S.D. of 5% or better.**

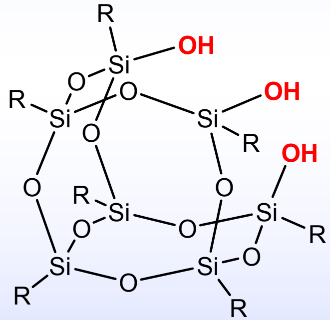
POSS: Where Are We Now (2004)

1996 data in red



- Cost: \$20-\$5000/lb (\$5000-\$1000/lb)
- Volume: Multi-ton (~20lb/yr)
- Production time: min 1 hour (11 days),

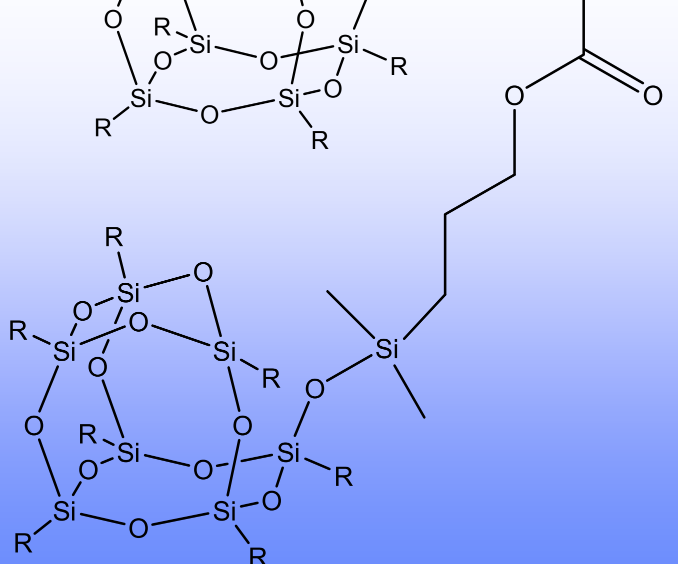
  max 14 days (6 months)



- Versatility: >120 POSS (36 POSS)

  monomers, feedstocks, polymers
- Many successful POSS blends
- Commercialized by Hybrid Plastics

  www.hybridplastics.com

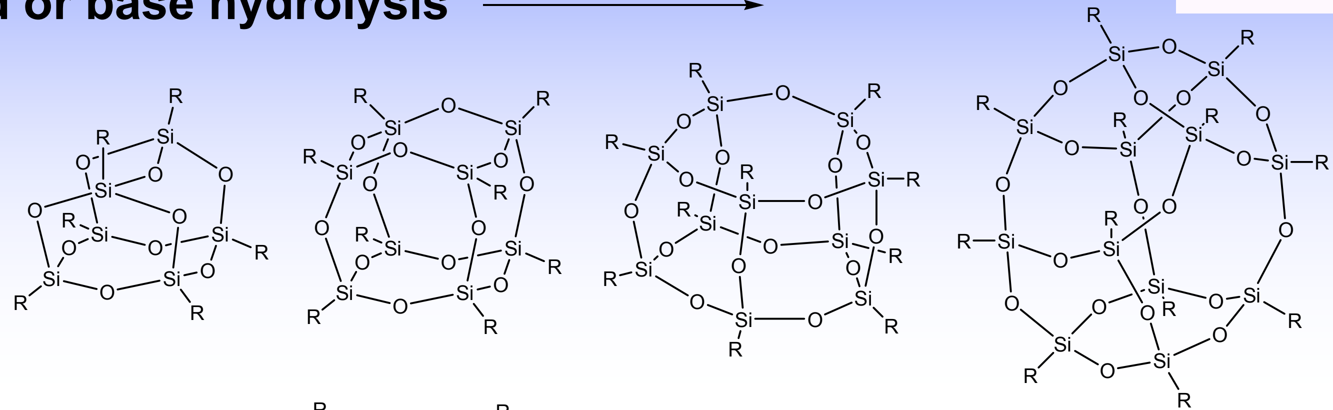


Polyhedral Oligomeric Silsesquioxanes (POSS)

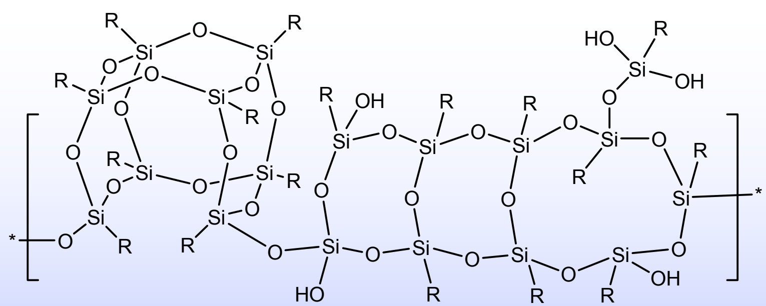
Hybrid Plastics™

$RSiX_3$ acid or base hydrolysis

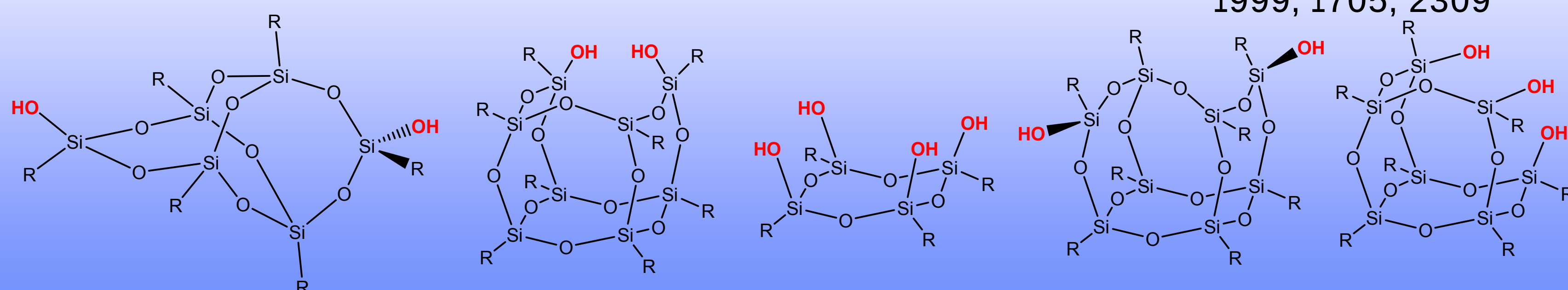
Blendables



Resin

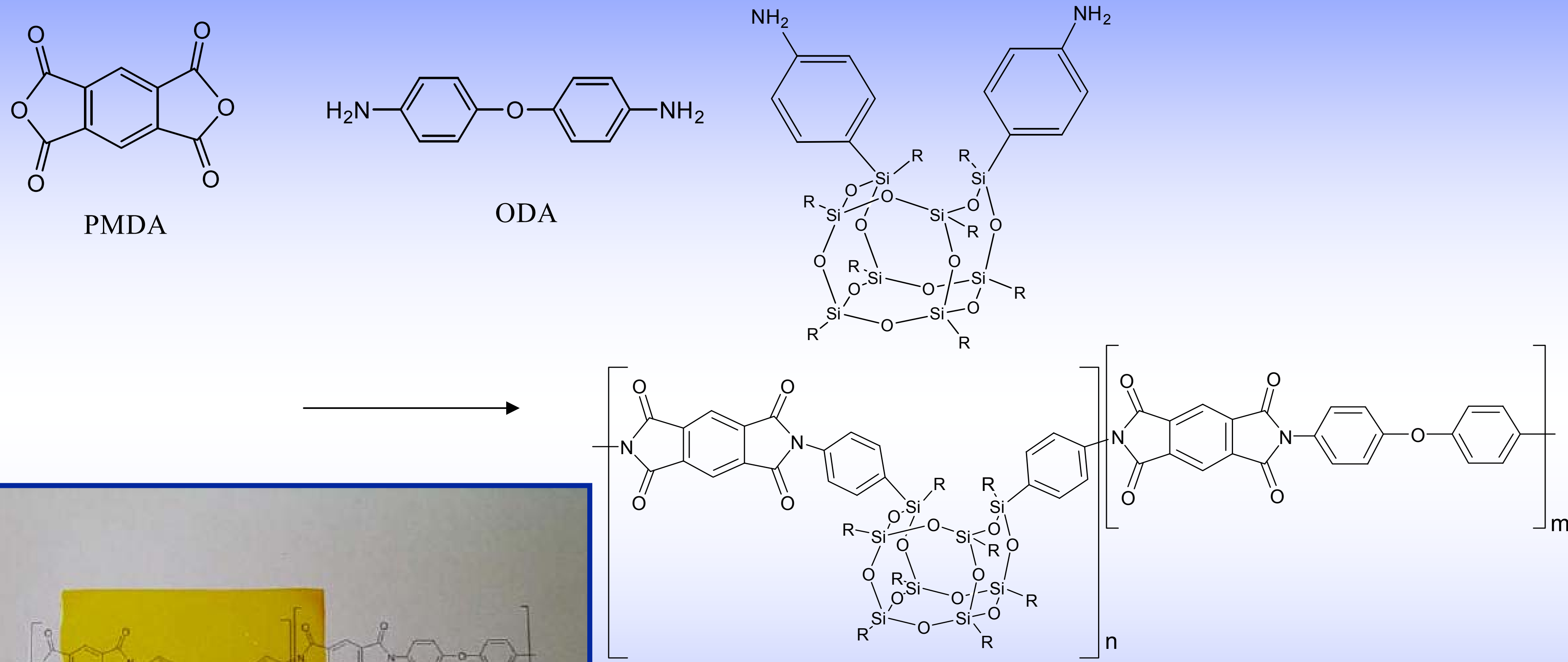


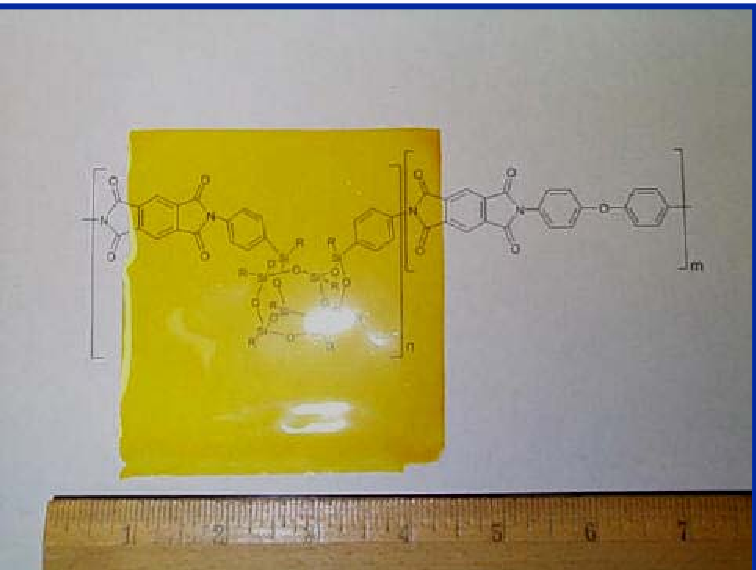
Brown & Vogt:
JACS, 1965, 4313
Feher et al:
JACS, 1989, 1741;
Organometallics, 1991, 2526; Chem Comm, 1999, 1705, 2309



Incompletely condensed cages

POSS-Kapton Polyimides



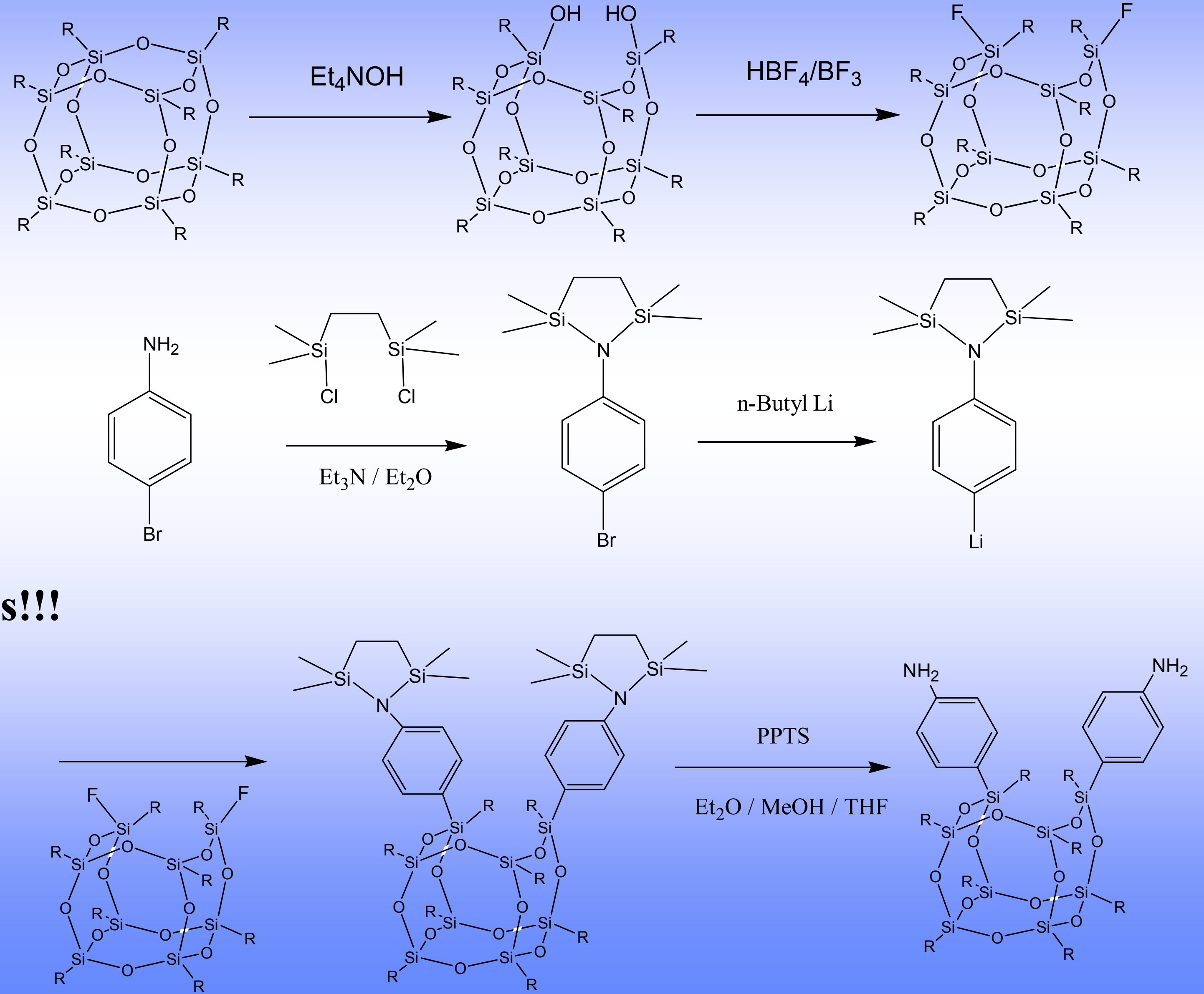


- **transparent films**
- **no aggregates formed**

First POSS-Aniline Synthesis

Multiple step synthesis
Moisture and air sensitive
Not amenable to scale up

Yet Critical for Development of POSS Polyimides!!!



DISTRIBUTION A.
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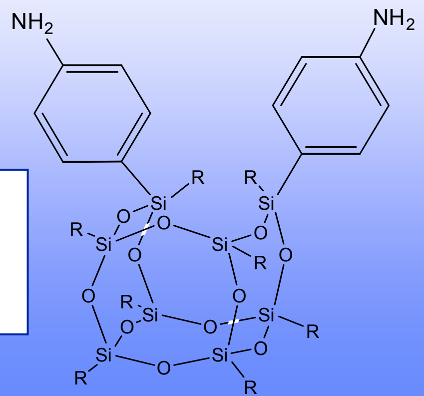
Program Challenge: Synthesis of Cost Efficient POSS Diamines.

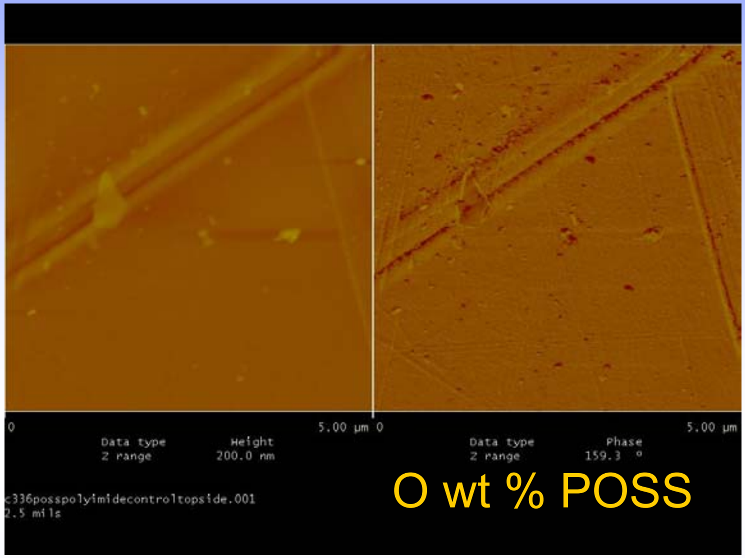
Make a cost efficient POSS Polyimide that is amenable to scale up and performs as well as current POSS Polyimide (POSSdi1 Polyimide).

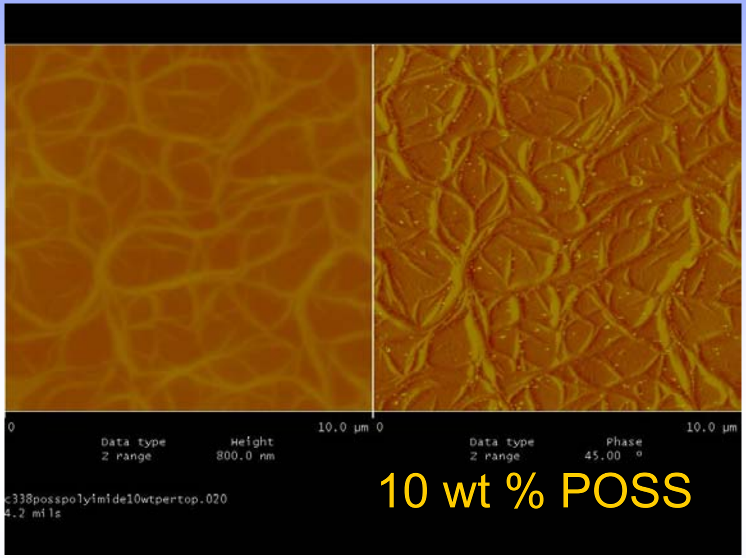
This will involve:

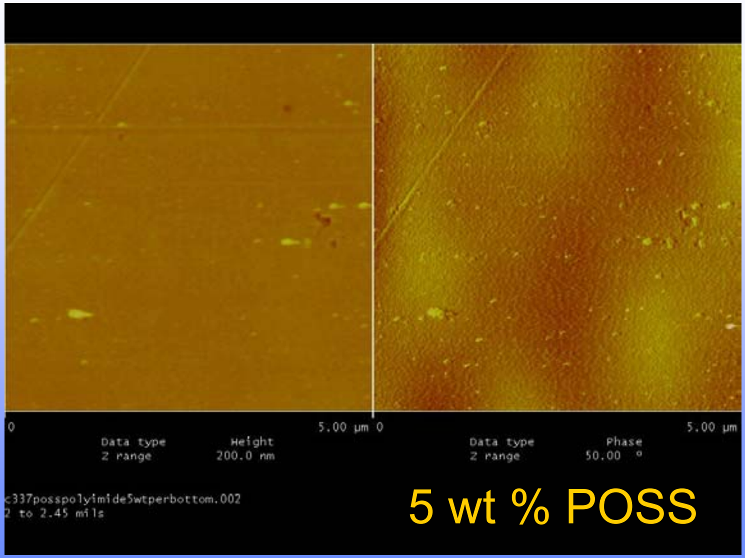
- Cost efficient synthesis of next generation POSS diamine monomers.
- Copolymerization of next generation POSS diamine monomers to form POSS Polyimides.
- Testing of thermal and mechanical properties and range of optical clarity.
- Imaging of POSS Polyimide films: Atomic Force Microscopy (AFM), Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM) with X-Ray mapping.
- Molecular modeling and simulation of oxygen atom, photon, electron, and proton attack on next generation POSS Polyimides.
- Simulated LEO and GEO exposure ground based testing.

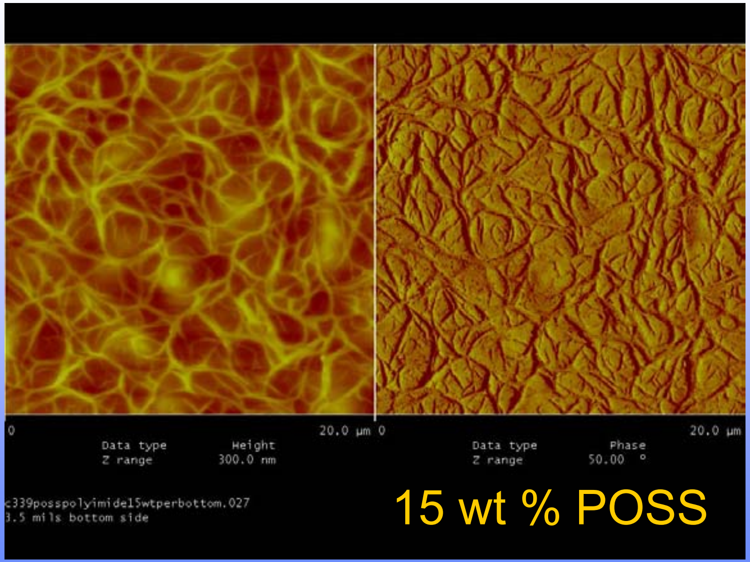


AFM Images of Unexposed Polyimides Copolymerized With Various Weight Percents of POSS

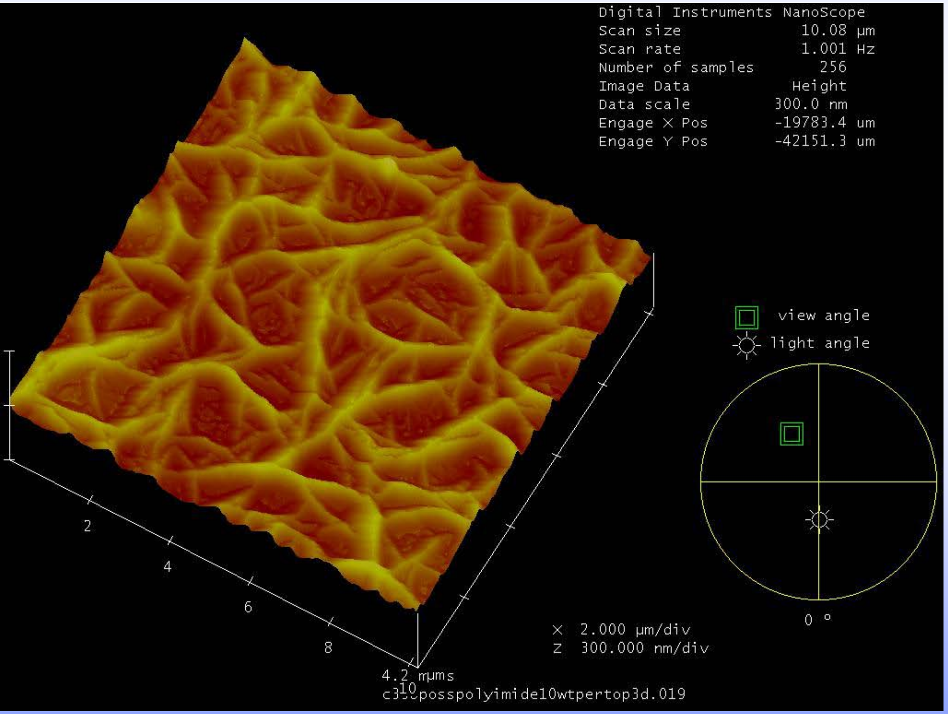


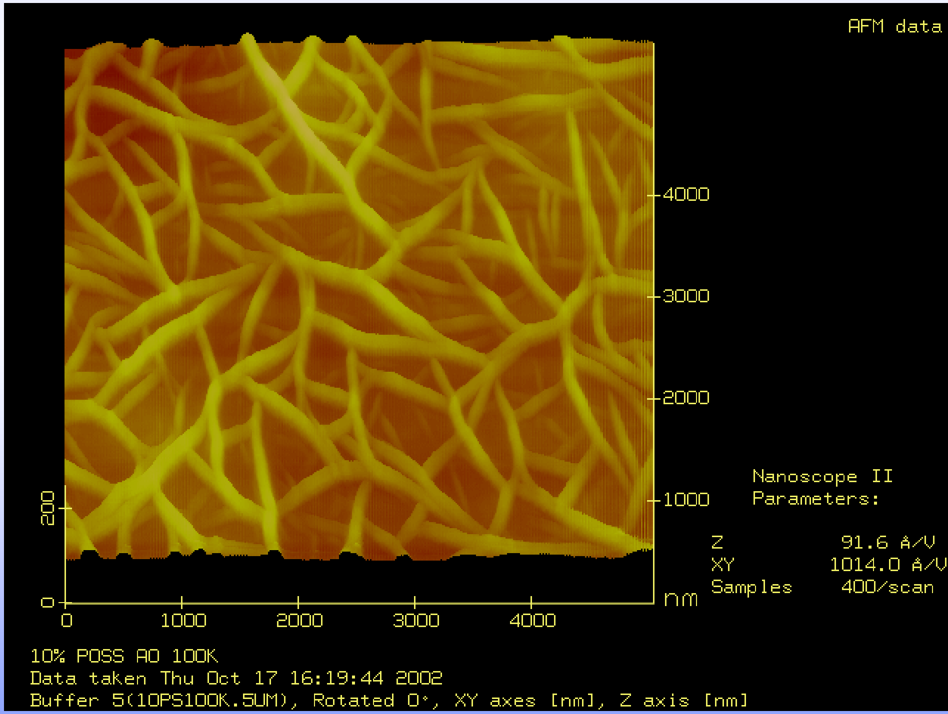






Three dimensional AFM Images 10 wt % POSS Polyimide Films



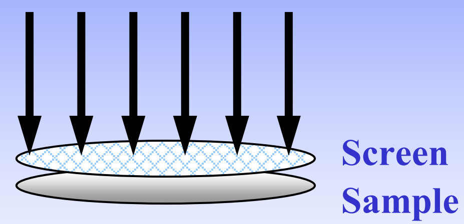


Unexposed

Exposed

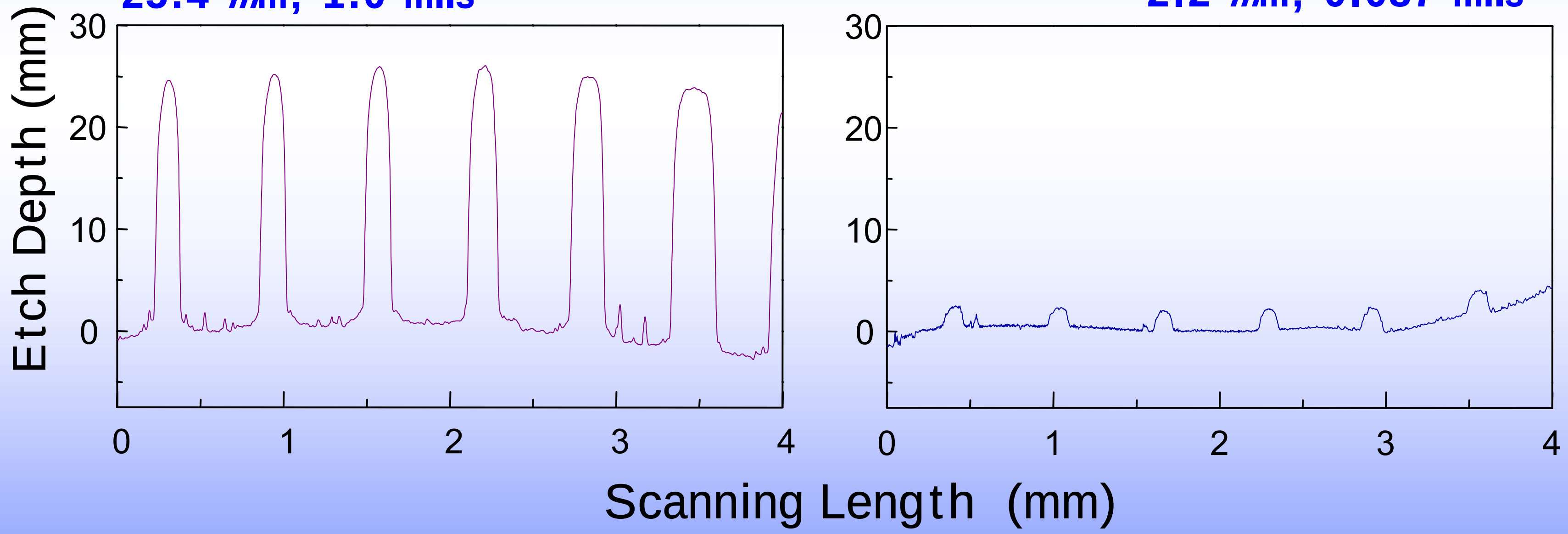
O-Atom Etching Experiment

Total AO fluence of 8.47 x 10^{20} atoms cm^{-2} (100,000 pulses)



Kapton H Standard
Average etch depth:
25.4 mm; 1.0 mils

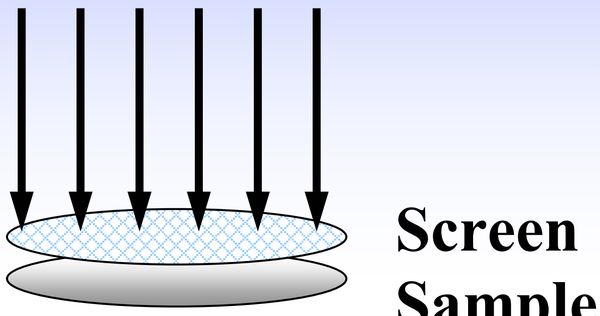
Kapton 10 wt% POSS
Average etch depth:
2.2 mm; 0.087 mils

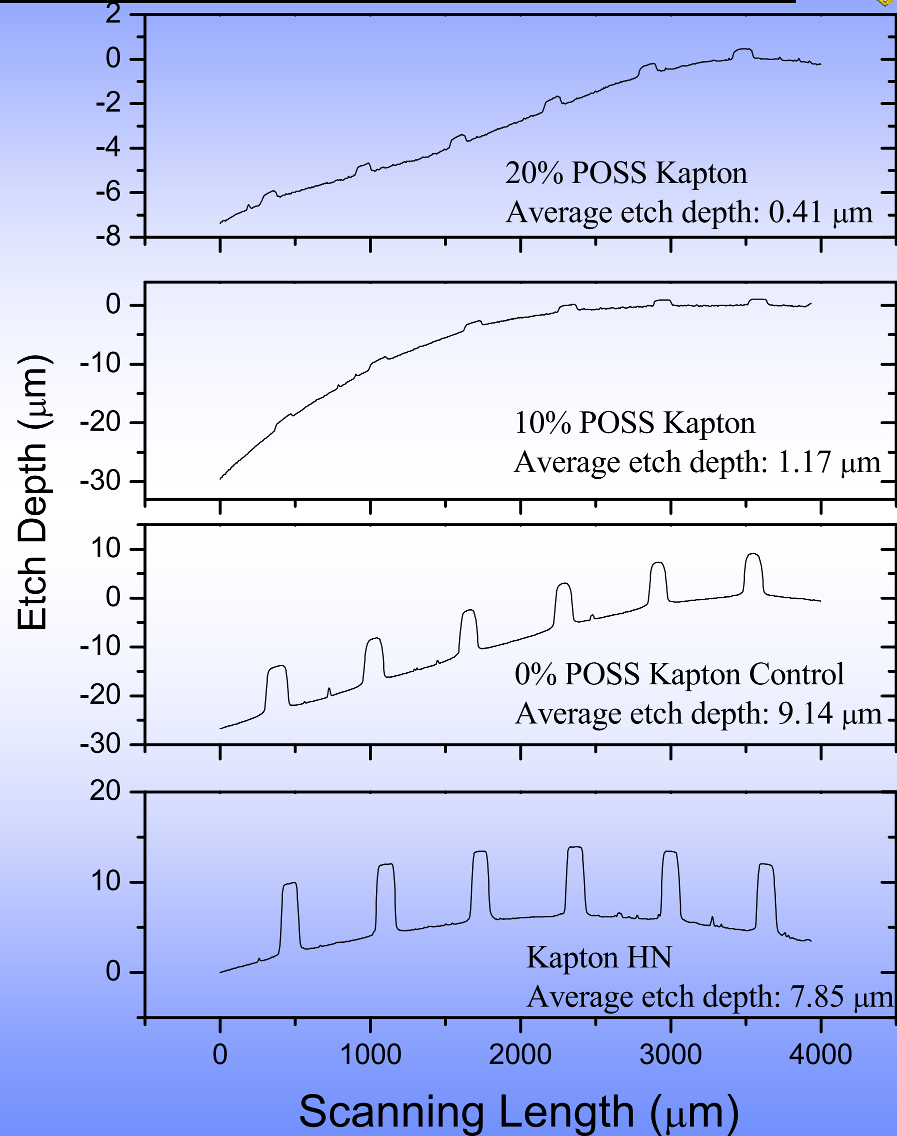


Significantly improved oxidation resistance due to a rapidly formed ceramic-like, passivating and **self-healing** silica layer preventing further degradation of underlying virgin polymer.

O-Atom etching experiment of POSS-Kapton polyimides
Total AO fluence of 2.62×10^{20} atoms/cm^2 (~ 3 Days in LEO)

Hyperthermal AO Beam



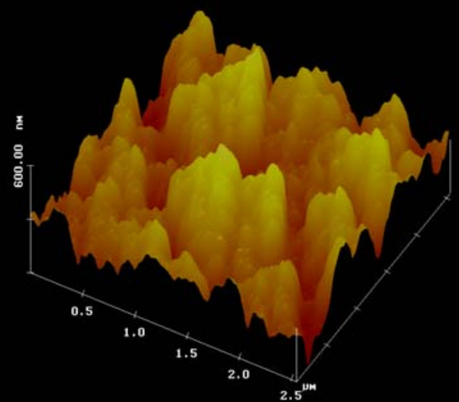


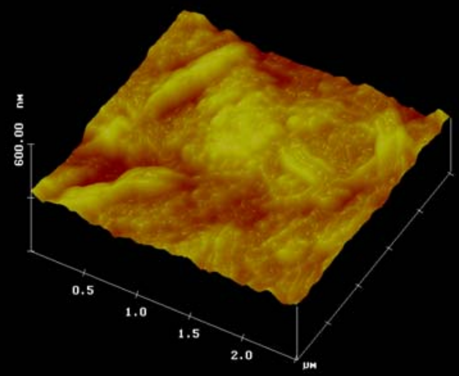
20 wt% POSS in Kapton results in over 20 time improvement in erosion resistance.

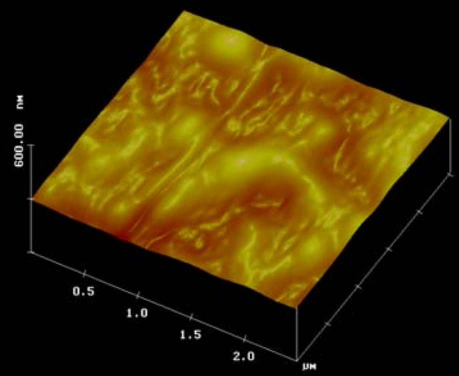
MONTANA STATE UNIVERSITY
BOZEMAN

AFM Images of Exposed POSS Polyimide Films 100,000 Pulses of Hyperthermal (5 eV) AO Beam

AFM Images of Unexposed POSS Polyimide Films







0% POSS

rms roughness: 11.09 nm

10% POSS

rms roughness: 1.7 nm

20% POSS

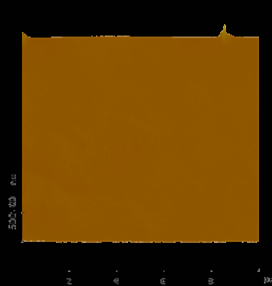
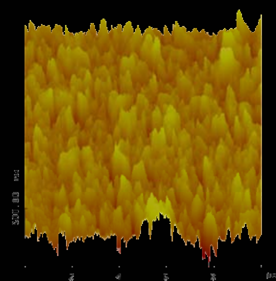
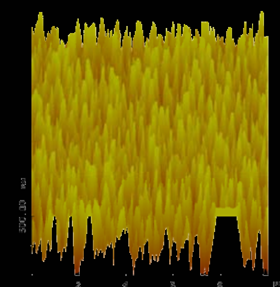
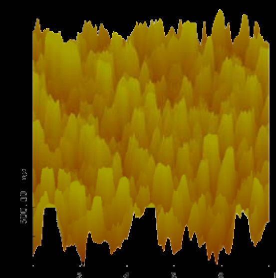
rms roughness: 16.5 nm

AFM Images of POSS Polyimides With increasing AO Flux.

(10 × 10 μm; z scale = 500 nm)

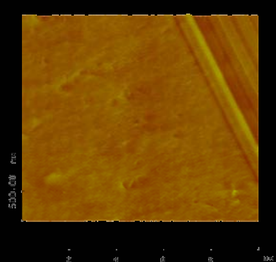
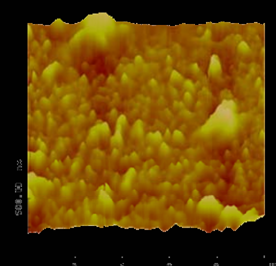
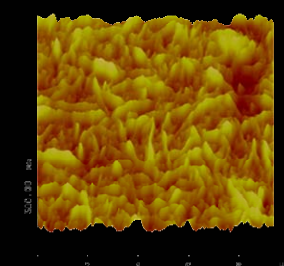
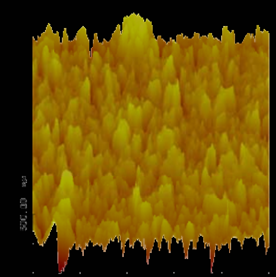
rms roughness → 2.48 nm | 70 nm | 120 nm | 126 nm

0 wt % POSS Polyimide →

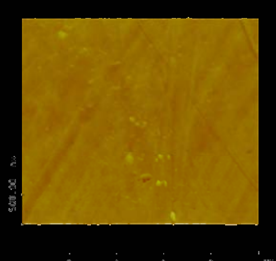
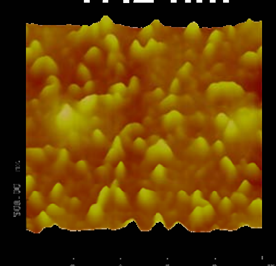
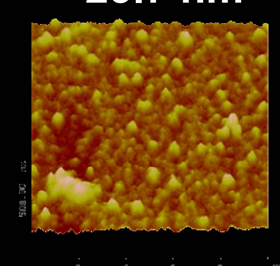
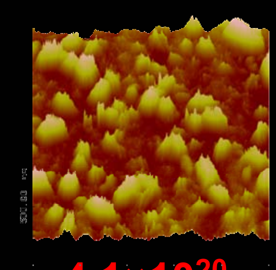
rms roughness → 2.47 nm | 22.4 nm | 34.3 nm | 78.9 nm

10 wt % POSS Polyimide →

rms roughness → 2.86 nm | 17.2 nm | 23.7 nm | 39.1 nm

20 wt % POSS Polyimide →

AO fluence (O atoms/cm^2) → $0.0\ cm^{-2}$ | 3.8×10^{19} | 1.6×10^{20} | 4.1×10^{20}

Note:

1×10^{20} O atoms/cm^2 is roughly equivalent to a spacecraft operating at 500 – 600 km orbit during nominal solar activity conditions for periods of at least 1 year.

X-ray Photoelectron Spectroscopy Analysis of POSS Polyimides

Surface Atomic Concentrations (%) determined from XPS Survey Scans following Atomic Oxygen Exposure

Sample	Exposure (beam pulses)	Kapton-equivalent atomic oxygen fluence (10^{20} O atoms cm^{-2})	C	O	Si	N
0 wt% POSS polyimide	0 6 100 250	0 ~0.1 1.63 4.10	72 69 69 55	19.5 20 24 36	1 2 1 0	7 9 6 9
10 wt% POSS polyimide	0 6 100 250	0 ~0.1 1.63 4.10	77 73 48 **20**	16 18.5 30 **56**	2 5 19 **23.5**	5 3.5 3 0.5
20 wt% POSS polyimide	0 6 100 250	0 ~0.1 1.63 4.10	70 66 20 **12**	20 24 54 **60**	6 7 25 **26**	4 3 0 1

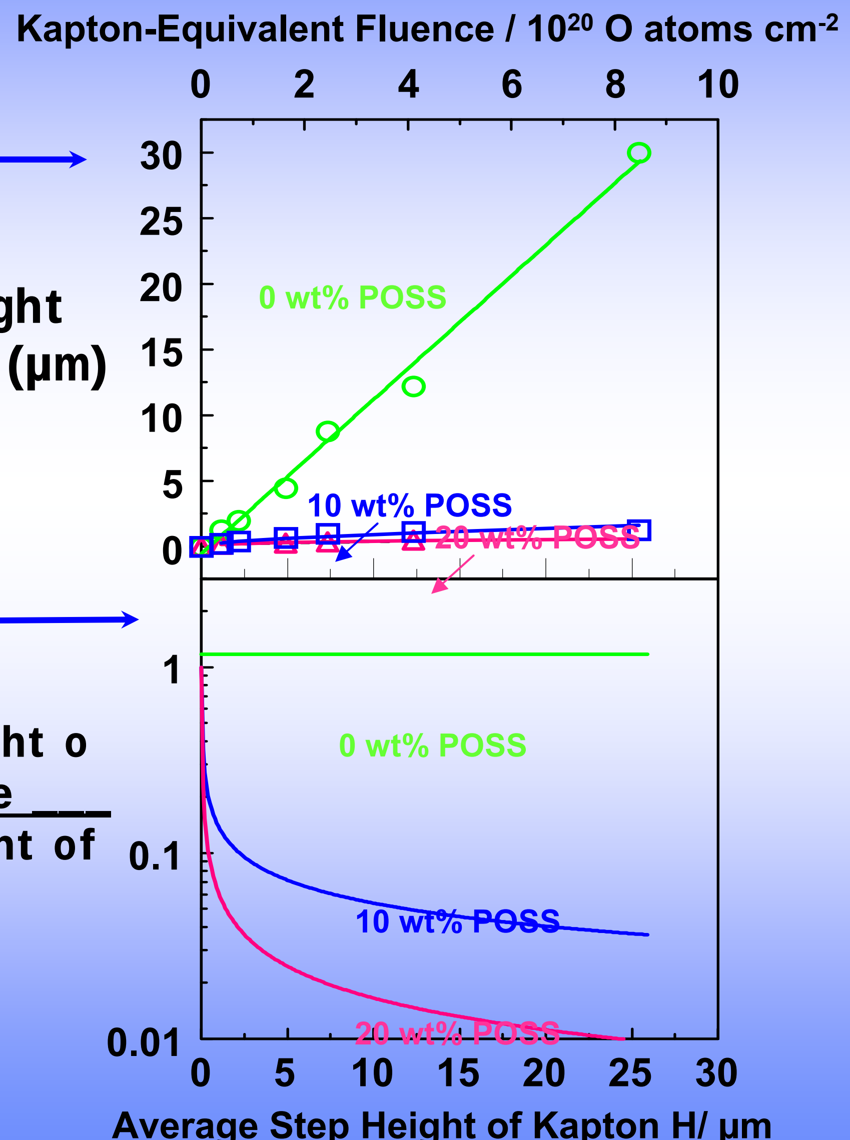
Erosion of POSS Polyimides by a Beam of Hyperthermal (5eV) O Atoms

Etch depths for 0, 10, and 20 wt % POSS Polyimide films as a function of O-atom fluence.

Average Step Height of POSSPolyimide (μm)

The erosion yields* of the 10 and 20 wt % POSS Polyimide samples were 3.7 and 0.98 percent, respectively, of the erosion yield for Kapton H at the highest fluence used in this experiment (8.5×10^{20} atoms cm^{-2}).

Average Step Height of POSS Polyimide / Average Step Height of Kapton H



$$\text{*Erosion Yield} = \frac{\text{erosion depth step height (cm)}}{\text{AO fluence atoms/cm}^3}$$

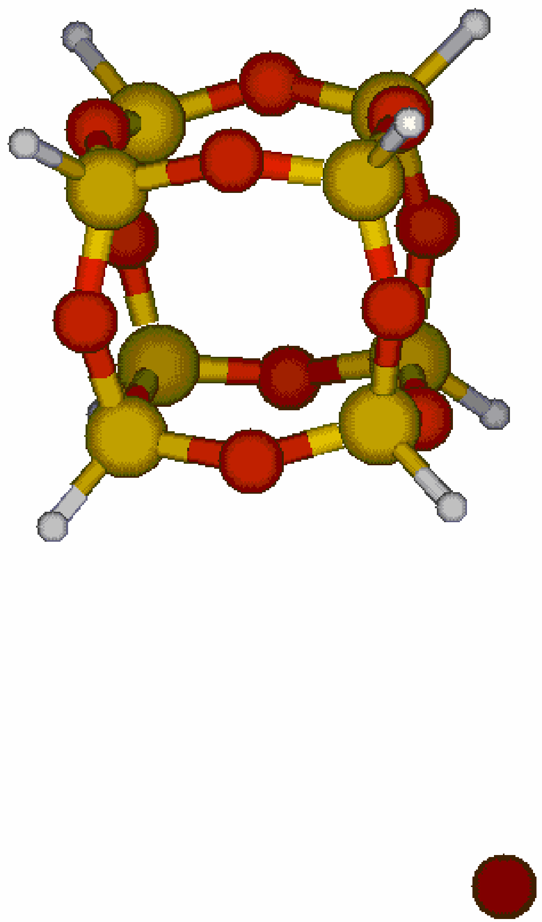
Molecular dynamics calculations of O(^{3}P) collisions (5 eV) with POSS ($Si_8O_{12}H_8$) cages

Possible Reaction Channels:

- H abstraction to give OH
- H elimination (O adds to the cage)
- Cage opening (O adds to the cage)

Number of trajectories	103
Impact parameter	7 a.u.*
Inelastic	63
H abstraction	3
H elimination	22
Cage opening	15

*(~Half diagonal of the Si_4 faces + 3 a.u.)

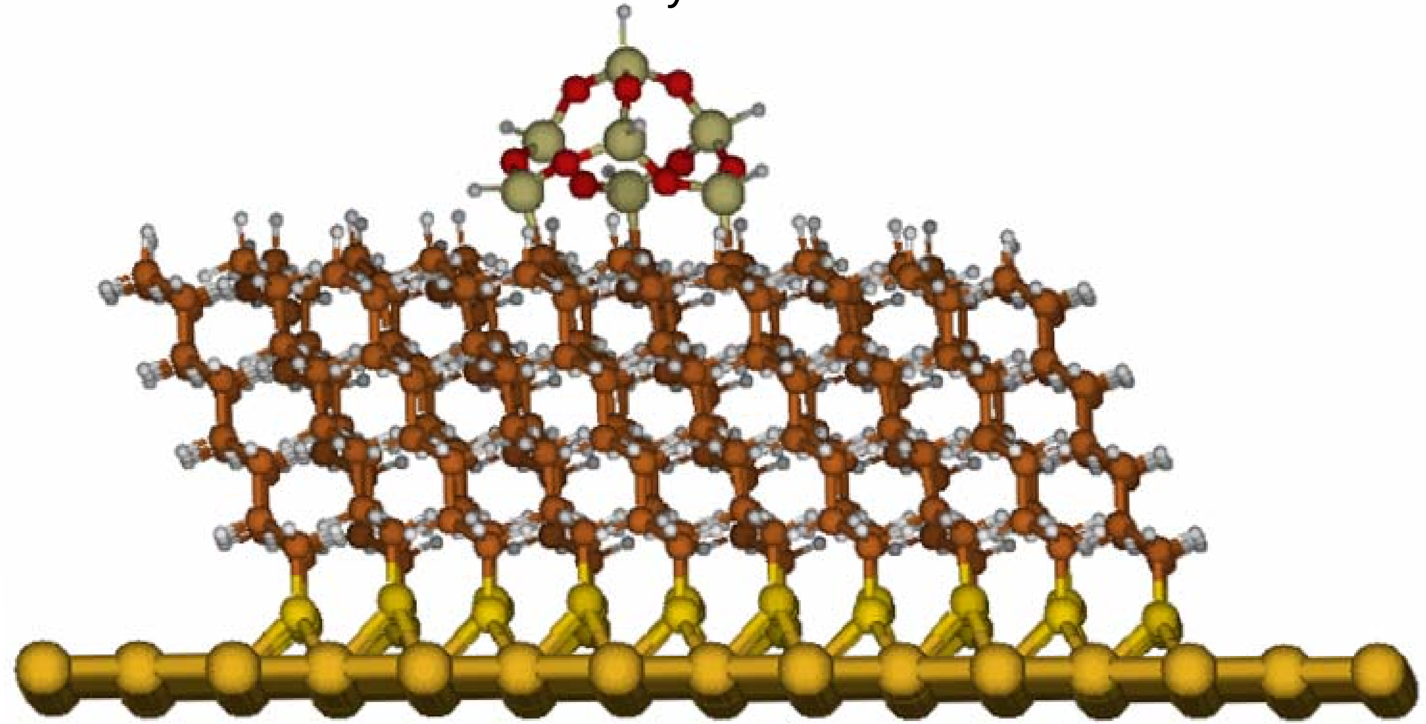


Model System: POSS Coated Alkane Thiol Self-Assembled Monolayer (SAM) on a Gold Surface.

➢Molecular dynamics calculations of O(^{3}P) collisions (5 eV) with “functionalized” POSS.

➢Method: Classical trajectories with a QM/MM (quantum mechanics / molecular mechanics) hybrid potential.

- QM part: O(^{3}P), POSS cage and 1st methylene unit of the bound chains.
- MM part: All of the SAM but the 1st methylene unit of the bound chains.



➢Results: Of limited trajectories studied, similar mechanisms of O atom attack on POSS ($Si_8O_{12}H_8$) Cages were found to apply to the studies of the POSS coated SAM.

Molecular Modeling Objectives

1. AO degradation pathways of polyimide when exposed to 5 eV oxygen.

2. Oxidation of POSS cage by 5 eV AO.

3. Penetration of 5 eV AO through POSS and silica layers to determine the SiO2 layer thickness needed to quench reaction with an underlying polymer layer.

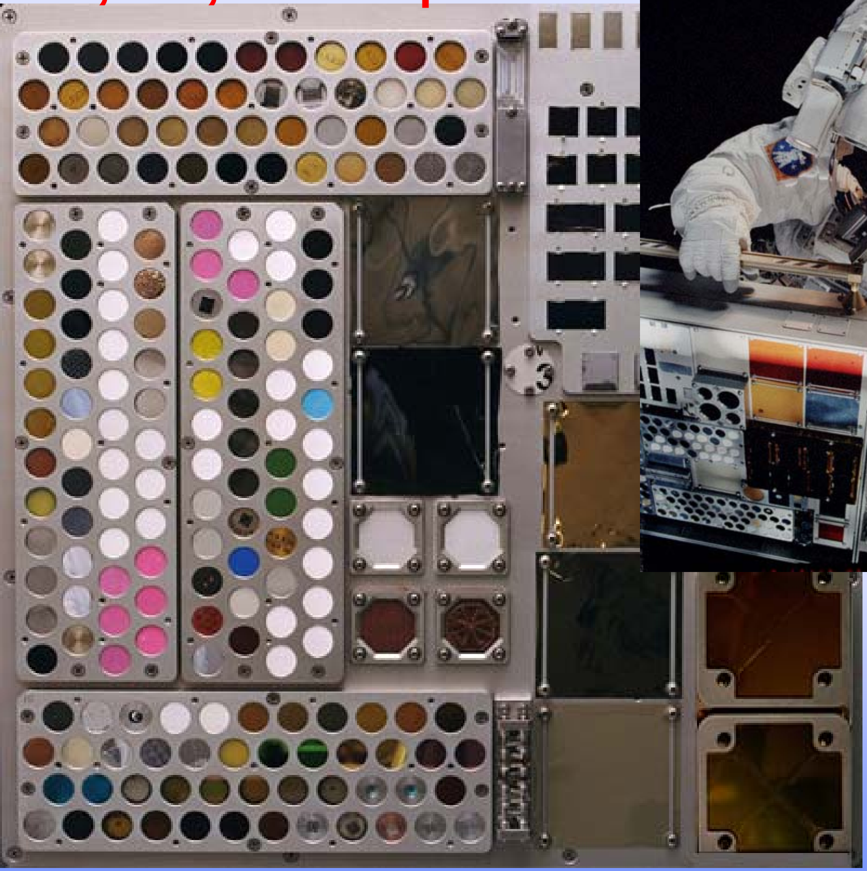
MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT

DISTRIBUTION A. Approved for public release; distribution unlimited.

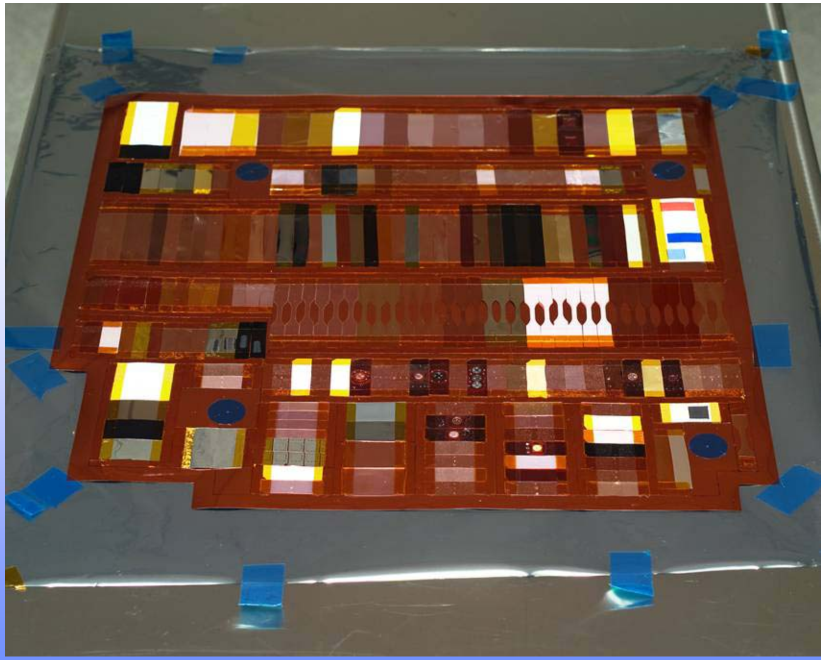
MATERIALS on the INTERNATIONAL SPACE STATION EXPERIMENT

POSS-Polymers Fly on STS 105 Discovery and are deployed on the International Space Station 16 Aug 2001, MISSE 4

AO, UV, VUV exposure.



POSS-Polymers awaiting flight on ISS, MISSE 5
<u>AO exposure only.</u>
<u>SALT Sprayed Samples!</u>

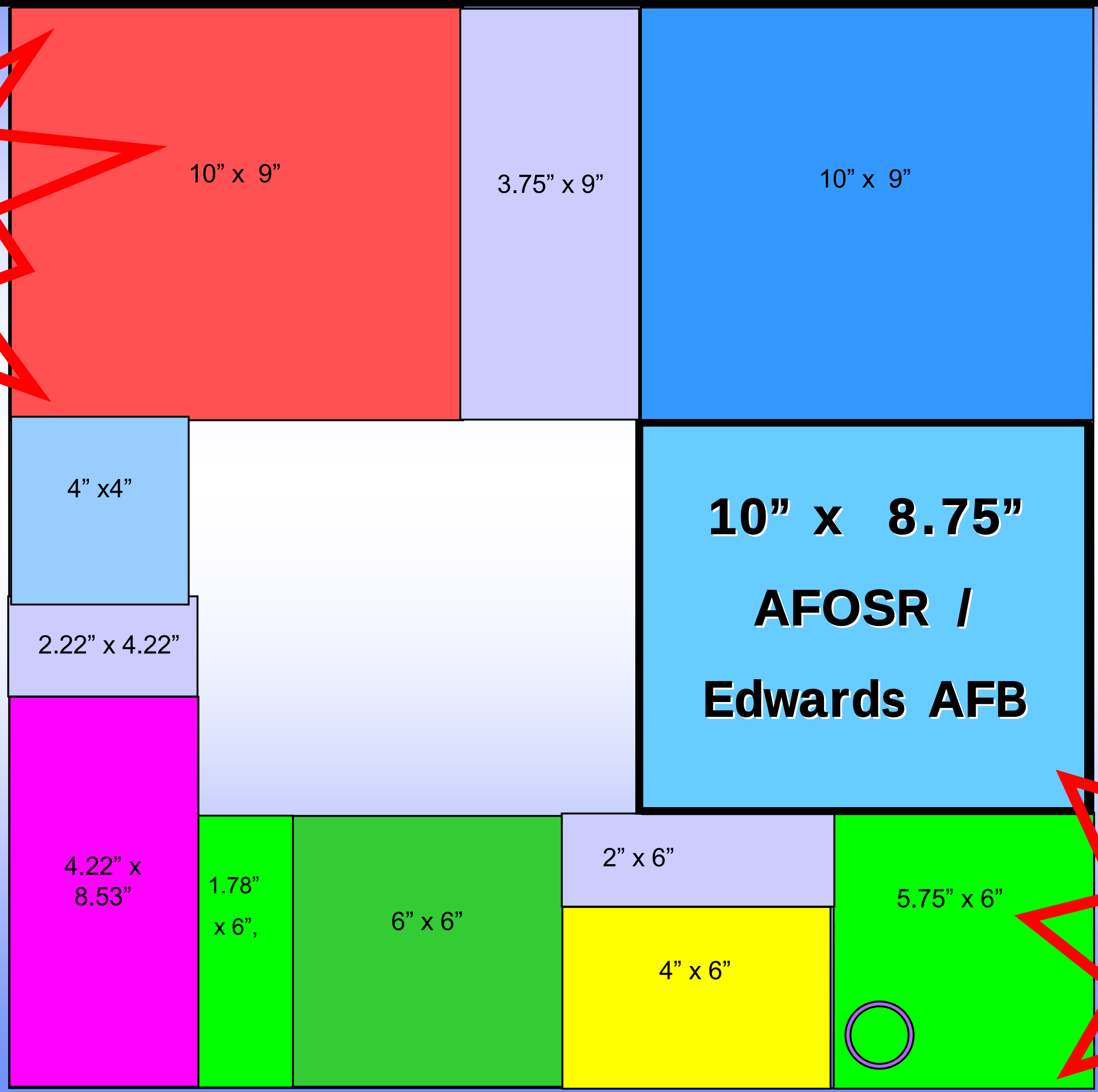


Footage courtesy of NASA

MISSE-6 Experiment Tray Layout: AO and UV Side

Data Loggers!

Quartz Crystal Microbalances!



Same amount of space on “UV only” tray!

Effects of POSS on Thermal and Mechanical Properties of Polyimides

- **POSS Polyimides do not lose rigidity** above the Tg.

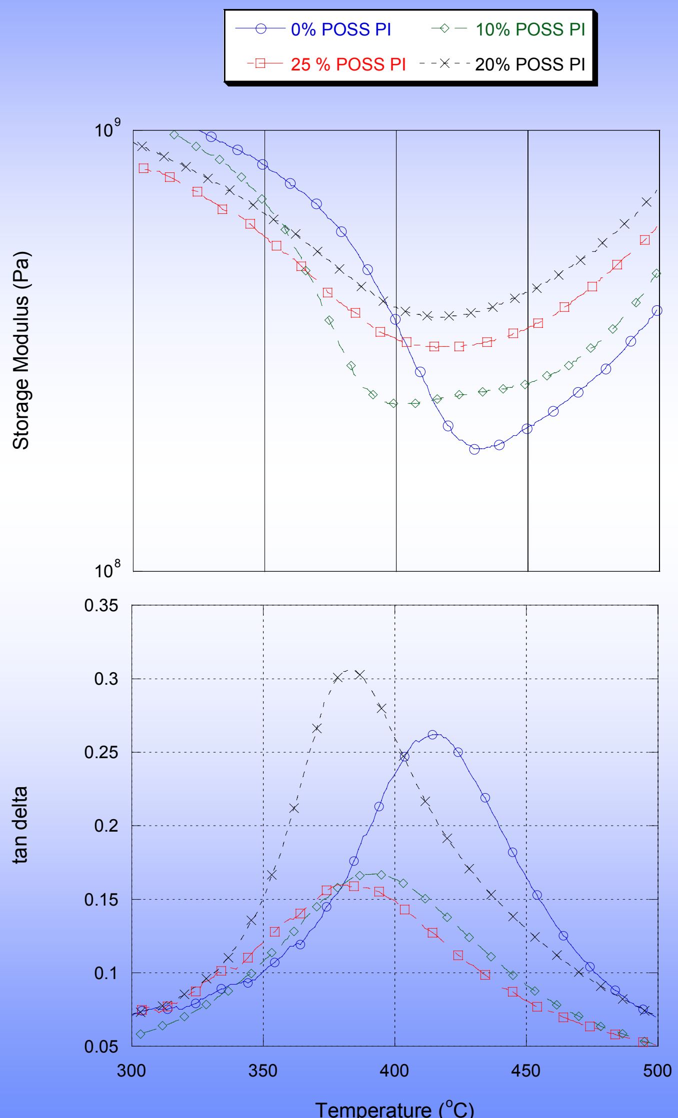
  Room temperature modulus (stiffness) unaffected by POSS.

  High temperature (430˚C) modulus exhibits a maximum with POSS PI loading at 20 wt%:

  @ 430˚C, the modulus of 20 % POSS Polyimide doubles relative to 0 % POSS polyimide.

- **Tg** of POSS polyimides is 5 – 10 % lower than polyimides (414˚C).

  Tan δ peaks for the 20 and 25 wt% are lower intensity and broader indicating that at POSS loadings greater than 20 wt% there exists interactions between the POSS molecules strong enough to significantly affect polymer chain dynamics.



Acknowledgments

Polymer Working Group: Dr. Tim Haddad, Dr. Joe Mabry, Mr. Pat Ruth, 2Lt. Laura Moody, Mrs. Sherly Large, 2Lt. Amy Palecek.

Previous Group Members: Capt. Rene Gonzalez, Ph. D.

Branch Chief: Dr. Shawn Phillips

Collaborators:

Aerospace Corporation; Dr. Mike Meschiznic, Dr Howard Katzman, Dr. Alan Hopkins, Dr, Gary Steckle
Hybrid Plastics
University of Montana State; Dr. Tim Minton
Northwestern University: Dr. George Schatz

Summary and Conclusions

- Our goal is to create an efficient drop-in replacement for Kapton that is:
  - Space survivable
  - Self passivating
  - Self healing
  - low in solar absorptance
  - Excellent in mechanical properties

- POSS Polyimides form a protective Si-O layer when exposed to Atomic Oxygen

- Modeling and Simulation Plan has shown that AO adds to the POSS molecule and does not pass through POSS.

- Thermal and Mechanical Testing indicate:
  - POSS Polyimides do not lose rigidity above the Tg.
  - Tg of POSS polyimides is 5 – 10 % lower than polyimides (414˚C).
  - Analysis of tan δ curves indicate that polymer chain dynamics are affected by the addition of POSS

- POSS-Polymers awaiting flight on ISS, MISSE 5 and scheduled to fly on MISSE 6.

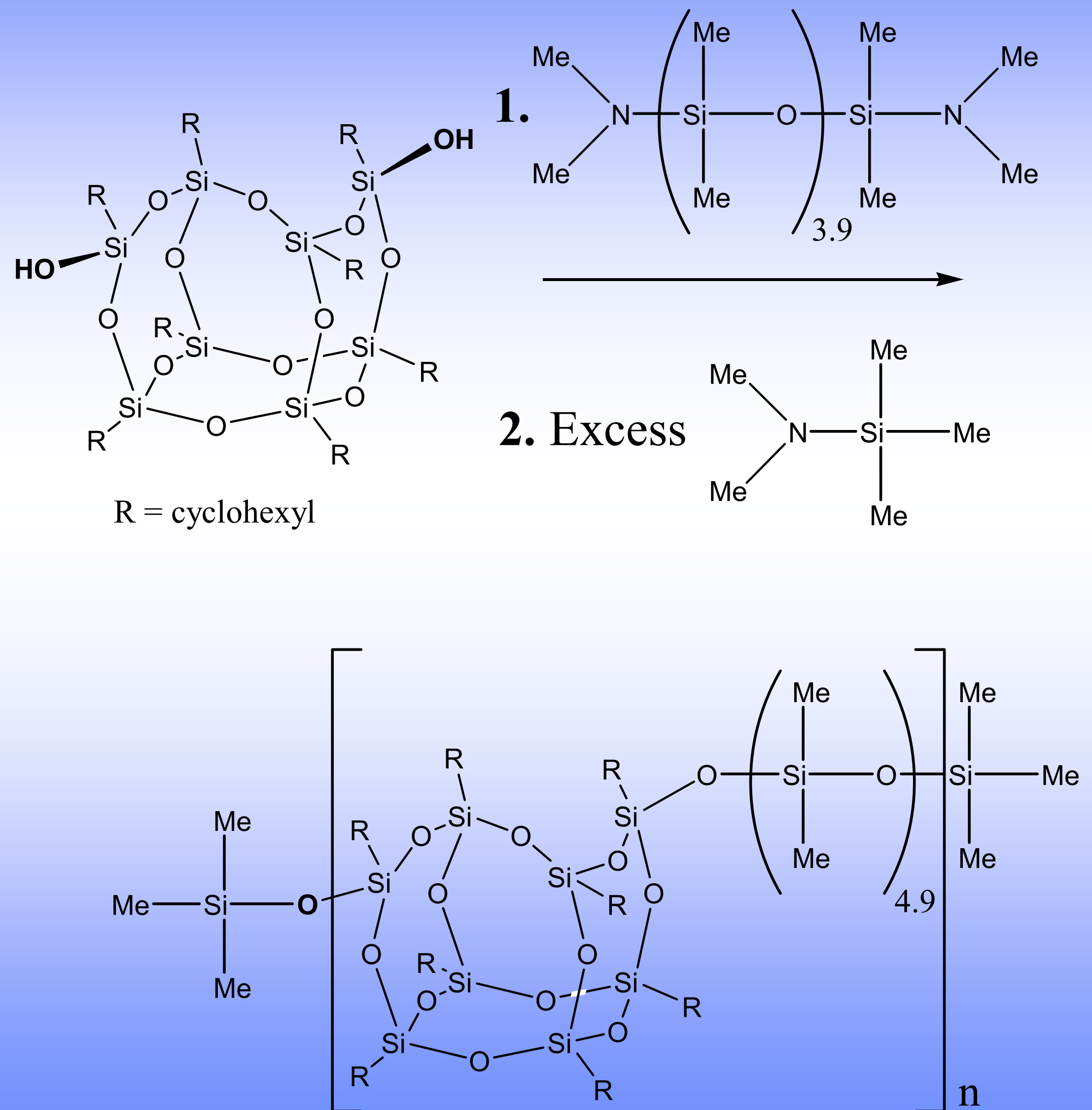
Abstract

Polyimides such as Kapton are used extensively in spacecraft thermal blankets, solar concentrators, and space inflatable structures. Atomic oxygen (AO) in lower earth orbit (LEO) causes severe degradation in Kapton resulting in reduced spacecraft lifetimes. One solution is that SiO_2 coatings impart remarkable oxidation resistance and have been widely used to protect Kapton. Imperfections in the SiO_2 application process and micrometeoroid / debris impact in orbit damage the SiO_2 coating leading to erosion of Kapton.

A self passivating, self healing silica layer protecting underlying Kapton upon exposure to AO may result from the nanodispersion of silicon and oxygen within the polymer matrix. Polyhedral oligomeric silsesquioxane (POSS) composed of a inorganic cage structure with a 2:3 Si:O ratio surrounded by tailor able organic groups is a possible delivery system for nanodispersed silica. A POSS diamine was copolymerized with pyromellitic dianhydride and 4,4′-oxydianiline resulting in POSS Kapton Polyimide. The glass transition temperature (Tg) of 5 to 20 weight % POSS Polyimide was determined to be 5 – 10 % lower than that of unmodified polyimides (414 ºC). Furthermore the room temperature modulus of polyimide is unaffected by POSS, and the modulus at temperatures greater than the Tg of the polyimide is doubled by the incorporation of 20 wt % POSS.

To simulate LEO conditions, POSS Polyimide films were exposed to a hyperthermal O-atom beam. Surface analysis of exposed and unexposed films conducted with X-ray photoelectron spectroscopy, atomic force microscopy, and surface profilometry support the formation of a SiO_2 self healing passivation layer upon AO exposure. This is exemplified by erosion yields of 10 and 20 weight % POSS Polyimide samples which were 3.7 and 0.98 percent, respectively, of the erosion yield for Kapton H at a fluence of 8.5×10^{20} O atoms cm^{-2}.

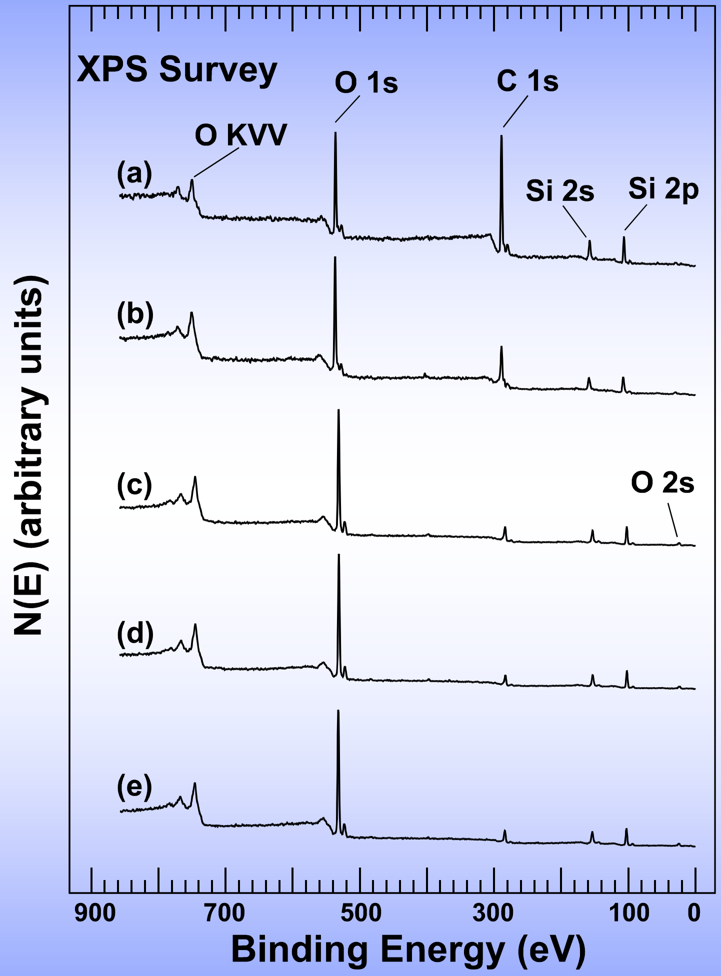
POSS - Siloxane

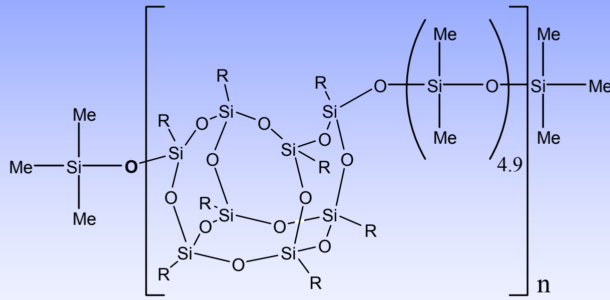


n = 43

POSS-PDMS Copolymer

POSS Siloxane





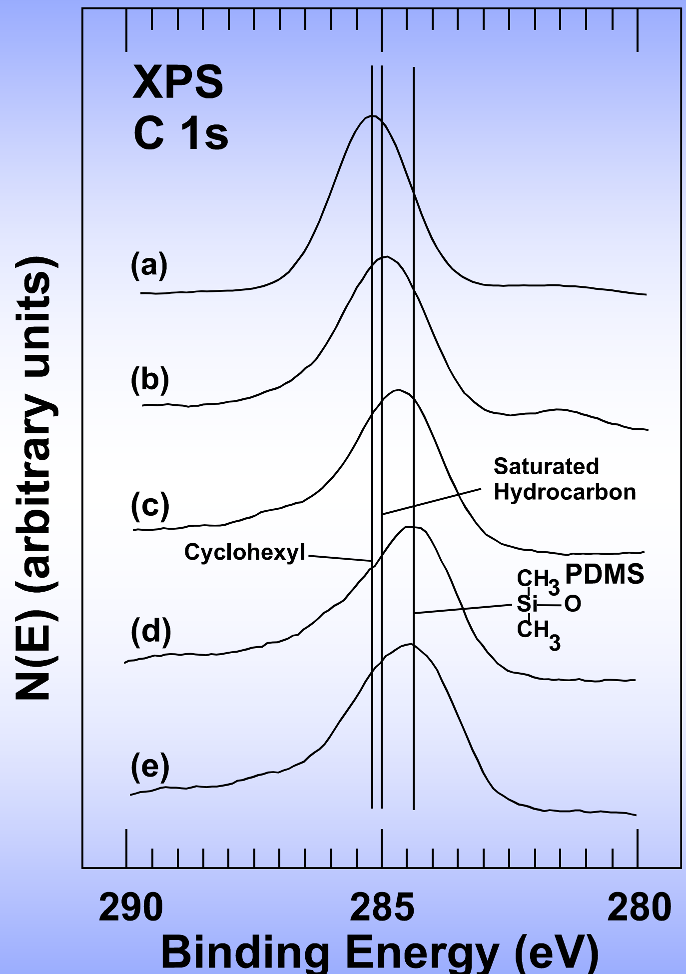
Composition, at %

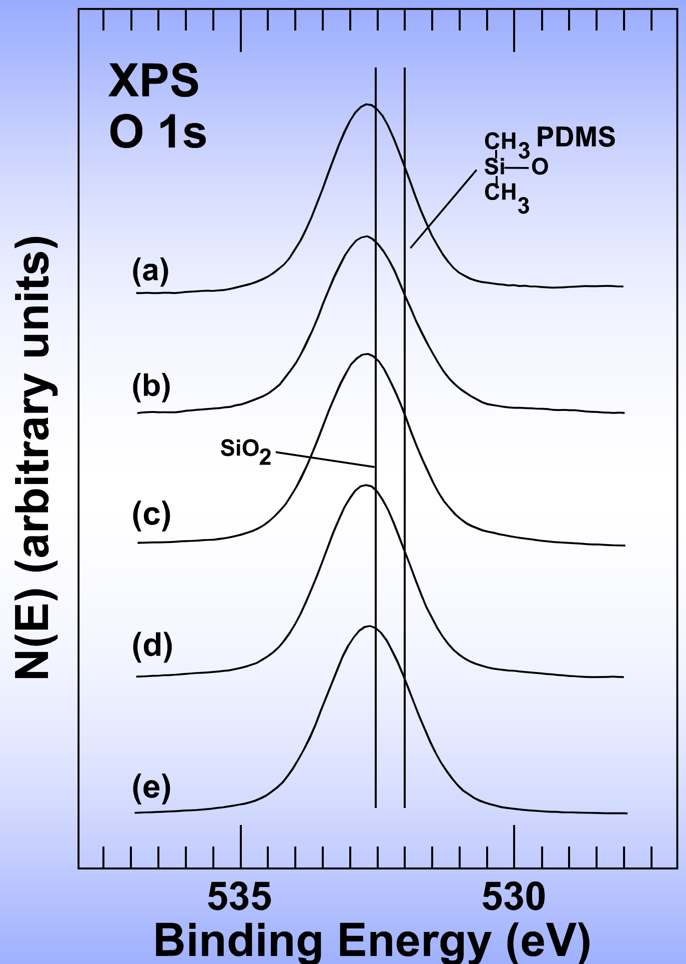
Sample Treatment	O	C	Si
As entered	18.5	65.0	16.6
2.0 hr	33.8	48.4	17.8
24.6 hr	49.1	22.1	28.8
63.0 hr	55.7	16.3	28.0
4.8 hr air	52.8	19.5	27.7

Gonzalez, R. I., Phillips, S. H., Hoflund, G. B., *J. of Spacecraft and Rockets*, Vol 37, No. 4, **2000**, pp. 463-467.

XPS survey spectra obtained from a solvent-cleaned, POSS-PDMS film (a) after insertion into the vacuum system, (b), after a 2-hr (c) 24.6-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 4.75-hr air exposure following the 63-hr AO exposure.

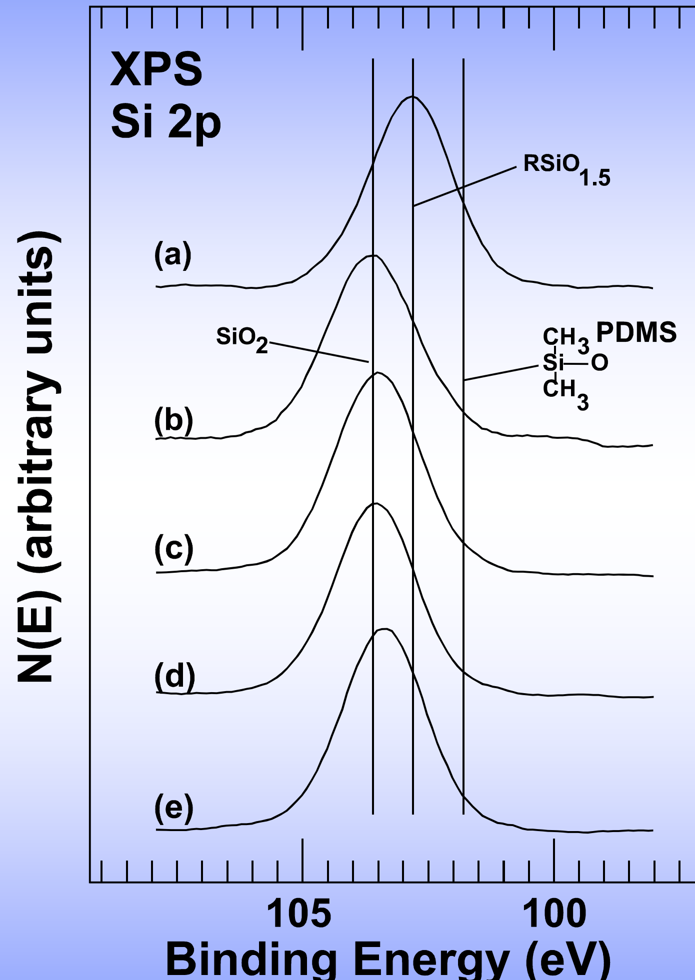
POSS PDMS





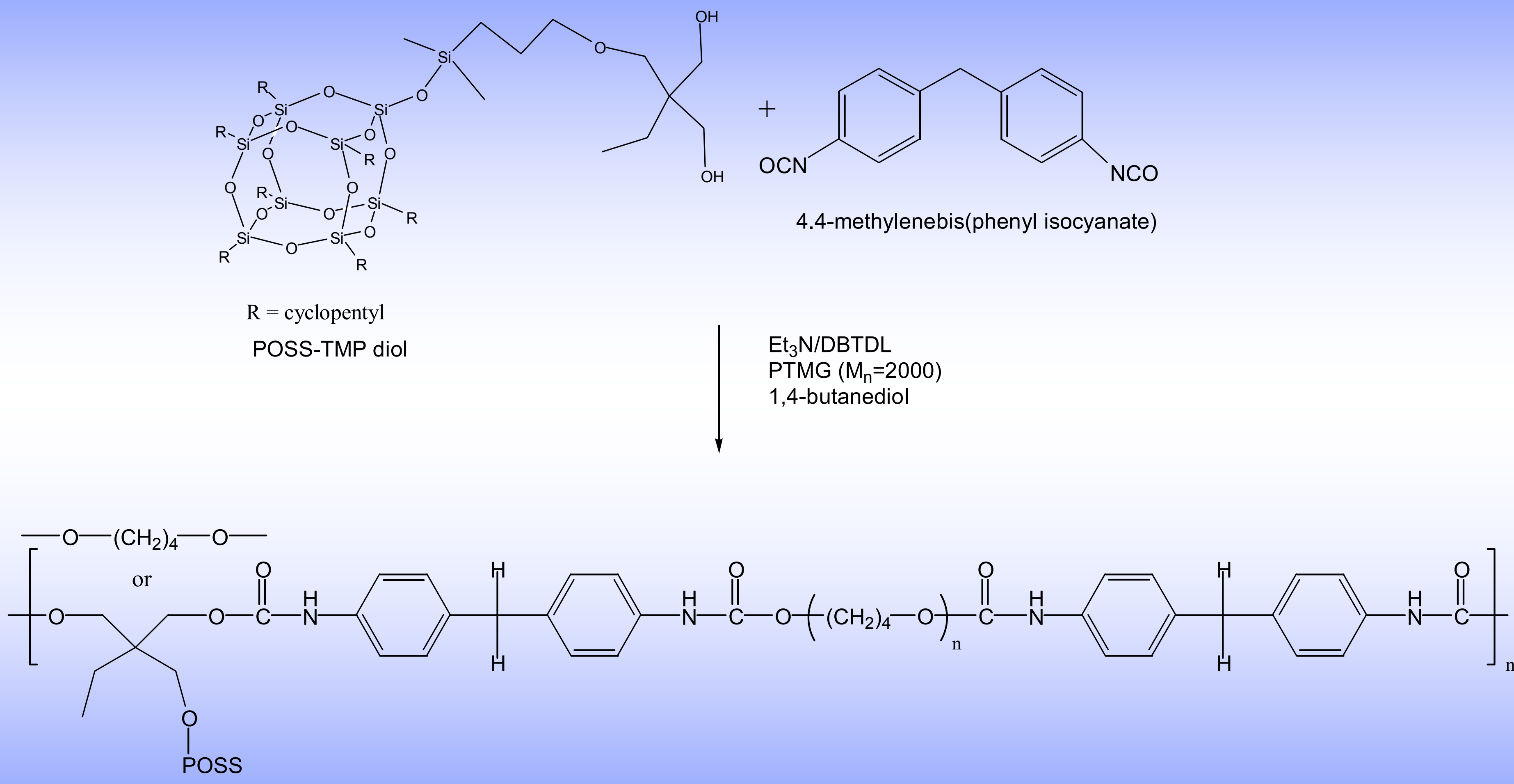
High Resolution C 1s and O 1s spectra obtained from a solvent-cleaned, POSS-PDMS film (a) after insertion into the vacuum system, (b), after a 2-hr (c) 24.6-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 4.75-hr air exposure following the 63-hr AO exposure.

POSS PDMS



High Resolution Si 2p spectra obtained from a solvent-cleaned, POSS-PDMS film (a) after insertion into the vacuum system, (b), after a 2-hr (c) 24.6-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 4.75-hr air exposure following the 63-hr AO exposure.

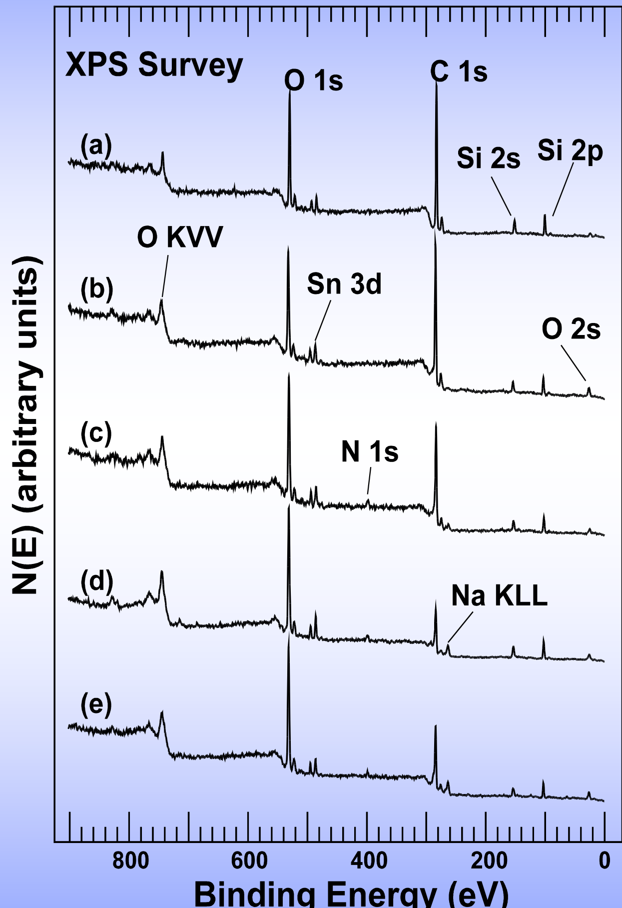
POSS-Polyurethane

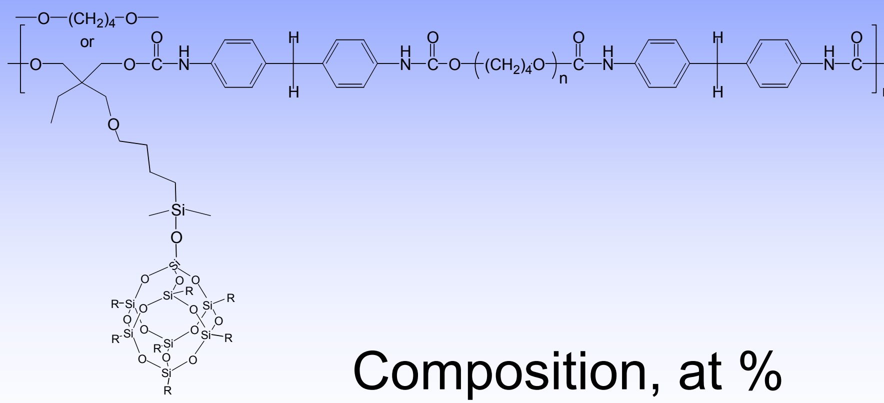


Fu, B.X., et al. *High Performance Polymers*, **2000**. 12(4): p. 565-571.

Fu, B.X., et al. *Polymer*, **2001**. 42(2): p. 599-611.

60 wt % POSS-Polyurethane

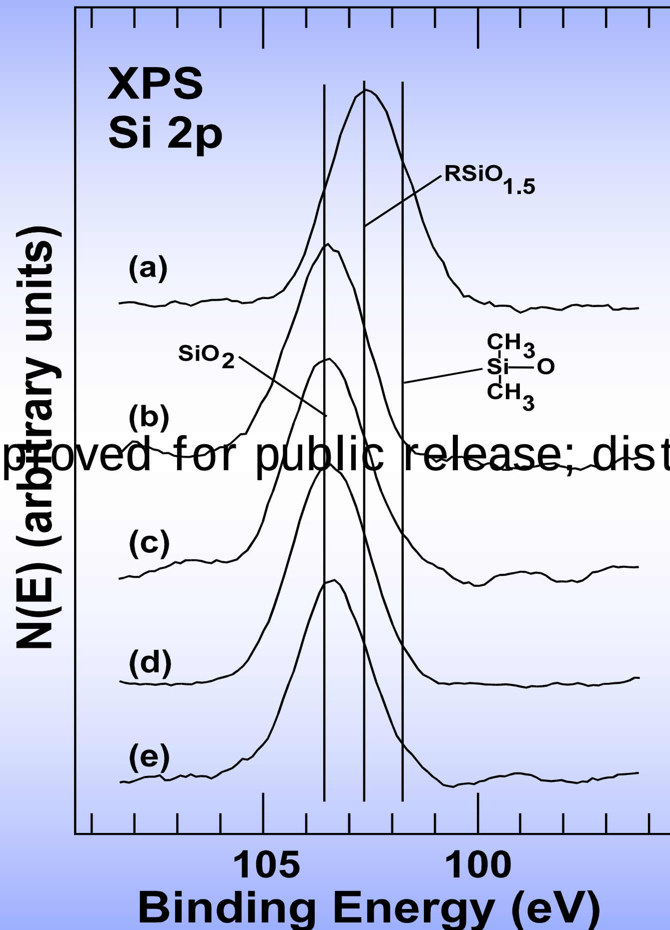




Composition, at %

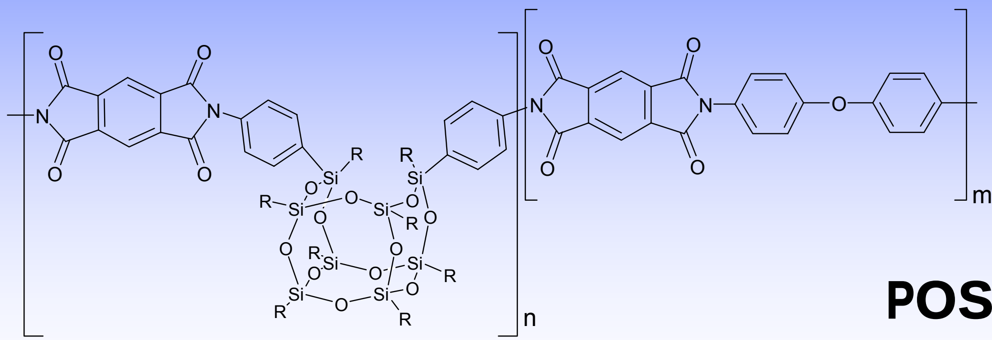
Sample Treatment	O	C	Si	Sn	Na	N
As entered	18.2	70.1	11.3	0.4	-	-
2.0-hr	17.5	70.2	11.2	0.7	0.4	-
24.0-hr	23.7	58.2	13.2	0.9	1.4	2.6
63.0-hr	35.3	37.3	20.4	1.3	3.0	2.7
3.3-h air	31.6	48.5	14.6	1.0	2.7	1.6

Phillips, S. H., Hoflund, G. B., Gonzalez, R. I., 45th International SAMPE Symposium, 2000, Vol. 45, No. 2, pp. 1921-1931.

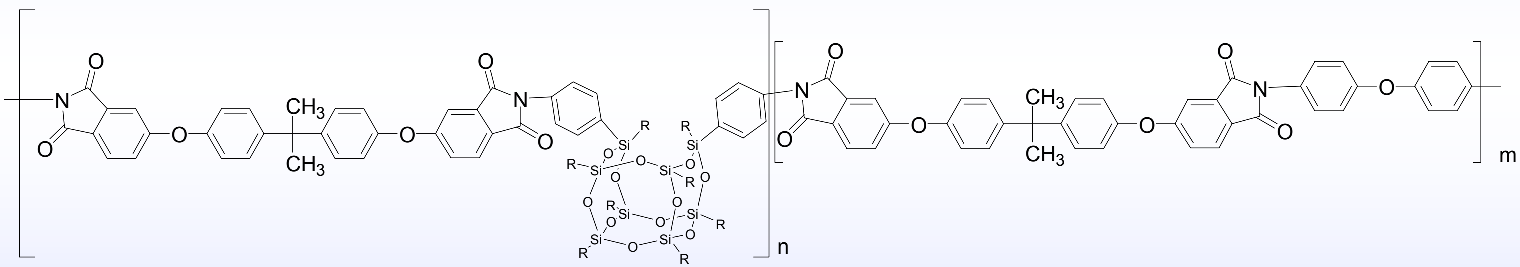


High Resolution Si 2p spectra from a 60 wt% POSS-PU (a) after insertion into the vacuum system, (b) after a 2-hr (c) 24-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 3.3-hr air exposure following the 63-hr exposure.

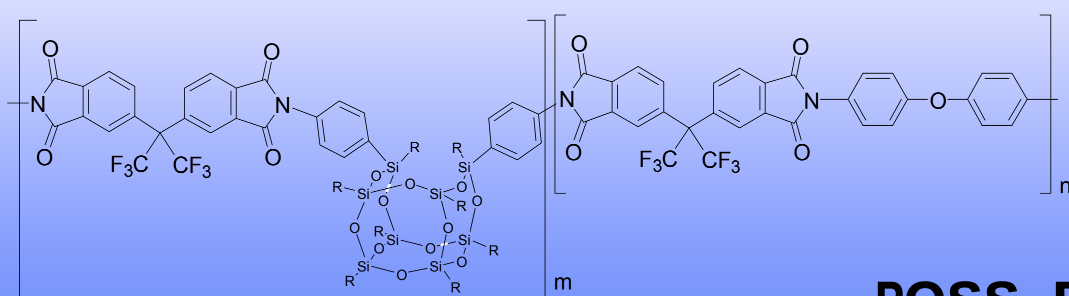
POSS High Performance Polyimides



POSS-Kapton polyimide



POSS processable ether-imide



POSS-Fluorinated colorless polyimide

POSS Polyimide

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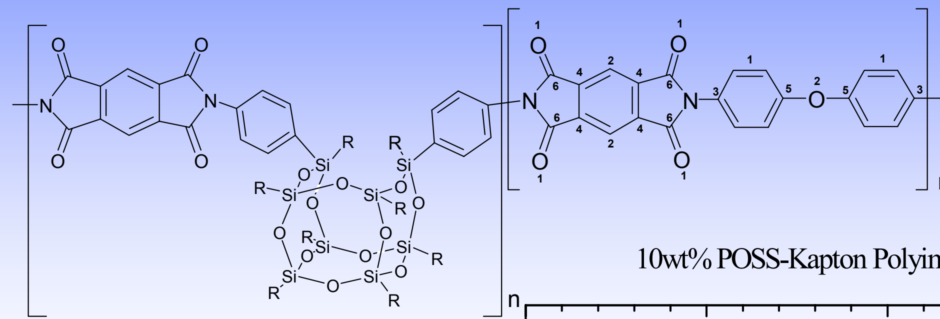
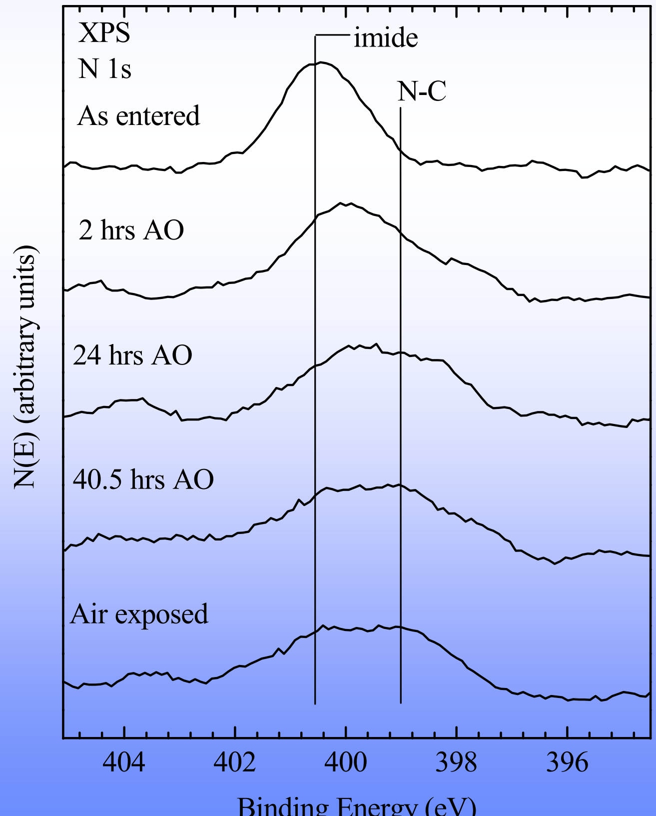


10wt% POSS-Kapton Polyimide



10wt% POSS-Kapton Polyimide